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NOTATION

g	acceleration due to gravity, 9.8 m/sec^2
$K_{(\ )}$	gain on ( ), units of driven quantity per ( )
L_v	dihedral effect stability derivative, rad/m-sec
M_u	speed stability derivative, rad/m-sec
u	velocity along body X-axis, m/sec
v	velocity along body Y-axis, m/sec
w	velocity along body Z-axis, m/sec
X,Y,Z	position coordinates, m
X_o,Y_o,Z_o	position coordinates at time zero, m
X_u	drag damping stability derivative, 1/sec
Z_w	heave damping stability derivative, 1/sec
$\varepsilon_{(\ )}$	error in ( ), units of ( )
θ,ϕ,ψ	Euler pitch, roll, yaw angles, rad
ω_n	undamped natural frequency, rad/sec

<u>Superscripts, subscripts</u>

$\cong$	approximately equal
$\sim$	proportional to
$(\ )^\circ$	degrees
$(\dot{\ })$	time rate-of-change of ( ), units of ( )/sec
$(\ )_c$	commanded value of ( ), units of ( )

<u>Abbreviations</u>

ADI	attitude/director indicator
AFCS	automatic flight control system
AGL	above ground level

CRT	cathode ray tube
CTOL	conventional takeoff and landing
FBW	fly-by-wire
FLIR	forward-looking infrared
FOV	field of view
fpm	feet per minute
fps	feet per second
ft	feet
HSI	horizontal situation indicator
HUD	head-up display
IEF	integrated electronic format
IFR	instrument flight rules
ILS	instrument landing system
IMC	instrument meteorological conditions
INS	inertial navigation system
IVSI	instantaneous vertical speed indicator
kt	knots
MLS	microwave landing system
PR	Cooper-Harper pilot rating
RPM	revolutions per minute
SAC	side-arm controller
SAS	stability augmentation system
SCAS	stability and control augmentation system
STOL	short takeoff and landing
VFR	visual flight rules
V/STOL	vertical or short takeoff and landing
VTOL	vertical takeoff and landing

SURVEY OF HELICOPTER CONTROL/DISPLAY INVESTIGATIONS FOR INSTRUMENT DECELERATING APPROACH

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SUMMARY

A survey of research and operational results concerning control-display requirements for helicopters conducting decelerating approaches in the terminal area under instrument meteorological conditions was conducted. In this report, the reviewed programs are organized primarily on the basis of the control augmentation concepts that were considered, and the salient results are summarized and compared. On this basis, nine control-display combinations are hypothesized as possible candidates for future ground and in-flight investigation. Specific guidelines for the guidance relationships, control characteristics, and display presentation concepts, as suggested from the review, are given.

1.0 INTRODUCTION

The expanding role of helicopter operations in both the civil and military sectors places increased emphasis on the need to define and develop an IMC (instrument meteorological conditions) capability for this class of aircraft. Recognizing this need, a variety of flight, ground simulation, and analytic programs has been conducted -- particularly in the past ten years -- to examine various aspects of the guidance, control, and display characteristics required to achieve this capability. The relationships among the results of these programs are often difficult to discern, however, because of the diverse approaches to the problem that were taken. Unfortunately, therefore, a clear understanding of which problems have been examined and which ones remain is often not obtained when a new study is initiated, and the new results may therefore either duplicate some previous work or be difficult to place in context with existing information.

This memorandum documents a study whose purpose was to identify, for future research, potential control/display configurations for helicopter IMC operations in the terminal area. In particular, the determination of these configurations was based in large part on an examination and organization of relevant information from previous work to ensure maximum utilization of existing knowledge. Toward this end, a literature survey was conducted which concentrated on research and operational helicopter experience since 1973; excellent reviews of data extant prior to that period are contained in References 1 and 2. The primary varibles examined and the salient results obtained as reported in the literature were summarized and compared to define generic guidance, control, and display characteristics plus their efficacy in providing an IMC capability; the emphasis was placed on concepts demonstrated in flight when possible, supplemented by ground simulator results. On this basis, recommendations for further investigation were developed.

The remainder of this memorandum is organized as follows. Section 2 outlines the IMC terminal area landing problem for helicopters in terms of the control loops to be closed and the guidance interfaces necessary. Section 3 reviews previous work, concentrating primarily on helicopter

flight demonstrations, and attempts to point out consistencies and discrepancies. Section 4 uses this information to hypothesize suitable combinations for future examination, and points out questions which still need answers. A bibliography of the documents reviewed for this study, including synopses of the applicable information from each, is given in the Appendix.

2.0 SUMMARY OF THE IMC TERMINAL AREA OPERATIONS PROBLEM

It is useful to summarize qualitatively the basic elements of the helicopter landing approach situation in order to provide a common reference for the remaining discussions. Trivially, the object is to take an aircraft to the landing spot from some initial position $X_0Y_0Z_0$ relative to the landing spot. For VTOL aircraft and helicopters, an additional requirement to decrease the speed to zero at the landing spot is introduced. This requirement means that the guidance function for helicopter approaches is intrinsically more complex than for CTOL aircraft: the command vector must include both commanded position and commanded velocity. Closed-loop guidance (either automatic or pilot) generally therefore requires knowledge of both current positions and velocities for the VTOL or helicopter approach.

To achieve the guidance-directed profiles, the helicopter pilot has four controllers which are, in the very short term, acceleration effectors in the aircraft axes: pitch, roll, yaw, and thrust magnitude. Qualitatively, the control situation (either automatic or by the pilot) is to control (and stabilize) aircraft attitudes (pitch, roll, heading) to command, in conjunction with thrust magnitude changes (and configuration changes for fixed-wing VTOL's), aircraft translational velocities, either to compare to guidance velocity commands or to integrate to compare to position commands. This qualitative loop-closure ordering offers a convenient means to assess both stability/control augmentation additions to the airframe and the amount/type of information that must be displayed to the pilot in manual control situations. It has been demonstrated in flight with the X-22A V/STOL aircraft (Reference 1) that, building on this control loop structure, a trade-off between

generic levels of control complexity and displayed information does exist for decelerating IFR approaches to hover. Hence, to some extent, deficiencies in either control characteristics or displayed information can be accounted for in the design of the other.

It is clear that the guidance, control, and display requirements can be heavily influenced by the approach task required and the environment in which the approach is performed. For decelerating approaches, the magnitude and direction of the wind plus the associated turbulence level is of major importance; factors unique to certain operations, such as ship airwake turbulence, are additional external disturbances against which the aircraft must be regulated to perform the guidance-commanded approach. The landing spot itself may introduce additional requirements, with the extreme case being a small pad on a moving ship. The choice of approach task (spatial geometry, deceleration characteristics) can also be expected to modify the guidance/control/display requirements. Finally, an obvious factor is the extent to which the approach is performed on instruments -- that is, when and if breakout to visual conditions occurs.

In discussing the research and operational helicopter IMC programs to be reviewed in the next section, it is useful to consider and compare the examined conditions according to these general concepts. The qualitative factors outlined above can be generally summarized in the manner given in References 1 and 3 and repeated below:

1. Task Variables

- initial velocity and altitude (representative of helicopters; representative of VTOL aircraft; civilian or military applications)
- localizer and glideslope interception (inclusion in task; procedure)
- approach trajectory geometry (straight; curved; flare included)

- range and/or altitude for breakout to visual conditions (all IFR; combination)

- deceleration values and profiles (level or descending; constant, exponential, or "optimized")

- wind and turbulence (crosswinds; headwinds; shears; shipwake)

- landing pad (obstacles; motion)

2. Guidance Information Variables

- available ground-based position information (none; azimuth and elevation; azimuth, elevation, and range; x, y, z, coordinates)

- translational rates (ground derived; aircraft derived; none)

- command references (ground or air; earth axes or aircraft axes)

- command relationships (range rate or deceleration vs range; command limiting; hover-oriented or functions of configuration)

3. Control System Variables

- unaugmented aircraft characteristics

- type of augmentation (angular rate; angular attitude; vertical rate; translational rates)

- degree of automation (none; automatic configuration change; partial or full coupling to guidance data)

- level of augmentation (time constants; frequency and damping; decoupling)

- control characteristics (gearings; force gradients; transport time lags)

- design philosophy (open-loop characteristics; optimal control; frequency separation)

4. Display Presentation Variables

- type and medium (separate or integrated; head up or head down; electromechanical or electronic; vertical, horizontal and/or profile)

- displayed information (positions; positions plus velocities; absolute or error information; control director information)

- symbology (analog or digital; choice of symbols; sensitivities)

- control director design philosophy (control "demand" or "command"; pilot-centered or closed-loop characteristics; command senses; frequency separation; pursuit or compensatory)

- additional information (configuration change)

This qualitative organization of the factors involved has been used, to some extent, in summarizing the information obtained from the literature, which is reviewed in the next section.

3.0 LITERATURE REVIEW

3.1 Basis for Discussion

A plethora of investigations, ranging from flight test of existing operational helicopter systems to paper studies for "advanced" control/display designs were reviewed in the literature survey. In order to relate the findings to each other, the pilot's control-loop structure

discussed in the last section can be used to separate the investigations on the basis of the loops and the controller either the control augmentation or the displayed information is designed to assist. The stability/control augmentation half of the situation is the more convenient, because the varieties involved are fewer than the display concept details that were investigated. In general, it will be seen that the investigated control system "types" fall into the following categories:

- angular rate damping in pitch and roll axes, no thrust axis augmentation, various directional axis assistance.

- attitude augmentation/command in pitch and roll axes, with or without thrust axis augmentation, various directional axis assistance

- translational rate augmentation in pitch, roll, and/or thrust axes, various directional axis assistance

- position (guidance) coupling to give automatic control of pitch, roll, and/or thrust axes

We therefore use this breakdown as the initial divisor of the literature that was reviewed.

In this context, it will be useful to have as a point of reference a summary of the Task III X-22A flight experiment (References 1 and 3). Although not directed specifically at helicopter approaches, the program examined generic control systems, similar to the categories given above, in combination with generic levels of displayed information for descending decelerating terminal area approaches under instrument conditions. A review of the results will therefore provide a baseline against which to compare the results from the literature to be reviewed in succeeding subsections.

The terminal area task considered in this flight program consisted of approaches at 7 1/2 degrees from 1800 feet AGL to a level-off at 100

feet AGL; the initial velocity was 100 knots, with a constant deceleration initiated on the glideslope to bring the aircraft to a hover over the landing spot. To emphasize the control-display requirements and interaction, the entire task was performed on instruments, including the hover.

Five types of stability/control augmentation in combination with five levels of displayed information were examined; these variations were "generic" in that the intent was to concentrate on assisting the pilot in the control-loop hierarchy either through simplifying his control task or through providing additional command information. The control types were:

- rate damping in pitch, roll, yaw
- attitude command pitch, rate-command-attitude-hold roll, turn-following or heading-hold yaw
- attitude command pitch and roll plus dual-mode yaw
- automatic thrust vector rotation plus the third system
- augmented and partially decoupled control of longitudinal and vertical translational velocity, attitude command roll, dual-mode yaw

The display variables were predicated upon an electronic head-down display with variable format. Levels of information were designed into integrated horizontal-vertical formats, with analog symbology used for all the data; the levels were:

- angular orientation plus glideslope error, range and localizer position information
- the first plus 3-axis control directors on a separate instrument
- the first plus rate-of-descent error (compensatory logic), plan-view ground velocity vector and commanded velocity (pursuit logic)

- the third plus one integrated control director for thrust magnitude (compensatory)

- the fourth plus two more control directors for pitch and roll stick (compensatory)

In addition, since the aircraft required configuration changes to rotate the thrust vector in order to decelerate, an additional display element was a thrust inclination command (using ON-OFF compensatory logic).

A variety of results were obtained in this flight program. Figure 1, taken from Reference 1, illustrates the majority of the pilot rating data obtained. Among the most salient conclusions drawn were:

1. For the task considered, a trade-off between stability/control augmentation and display presentation sophistication existed for generic levels of each, within certain minima.

2. Pitch and roll stick control directors are not required for a satisfactory control-display combination if attitude command augmentation in pitch and roll is provided.

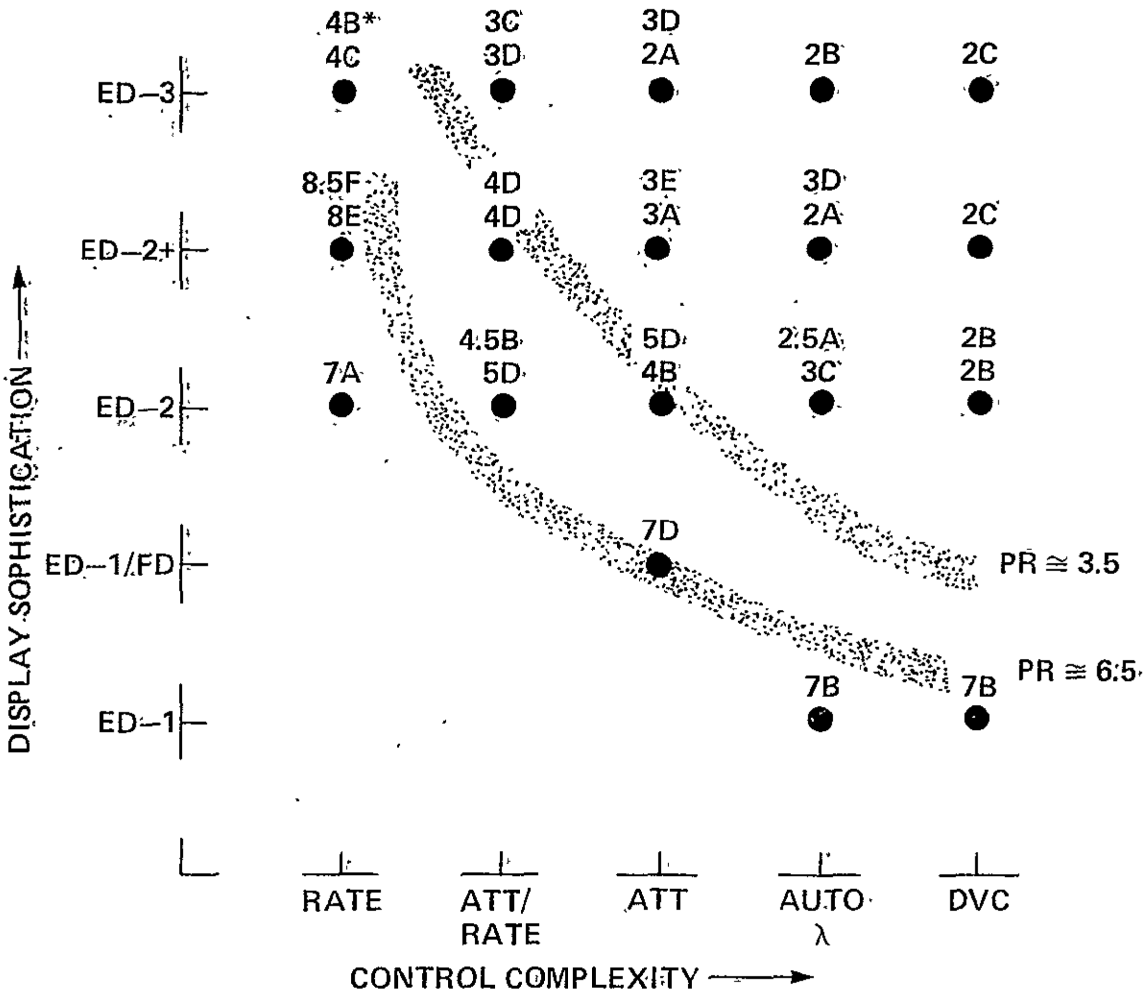
3. Improving the translational velocity control and response characteristics reduces the influence of displayed information nuances.

4. Explicit display of horizontal-plane translational velocity is required regardless of control augmentation.

5. A separate director command is required for precise manual thrust inclination scheduling.

6. Altitude tracking difficulties may be alleviated by providing a thrust magnitude control director, automating the configuration change, or improving the vertical velocity damping of the aircraft.

7. Angular rate augmentation control systems result in unsatisfactory control-display combinations for instrument hover regardless of displayed information.



*NUMBERS ARE COOPER-HARPER PILOT RATINGS, LETTERS ARE TURBULENCE EFFECT RATINGS. TWO RATINGS INDICATES TWO SEPARATE EVALUATIONS OF A CONFIGURATION.

Figure 1.- Pilot rating data for primary matrix (no crosswinds, with ITVIC), from reference 1.

8. A control-force-to-aircraft-attitude relationship is preferred to a force-to-attitude-rate relationship for instrument hover.

9. Augmenting the aerodynamic directional stiffness of the aircraft, when combined with roll attitude stabilization in particular, minimizes the influence of crosswinds on pilot ratings.

10. Pitch and roll attitude stabilization minimizes the effects of turbulence level on pilot ratings. For the control director design procedure used in this experiment, director response to turbulence could be high, thereby limiting their usefulness in reducing turbulence sensitivity.

11. Display of wind direction information would be beneficial regardless of the display or control system characteristics.

The following subsections review results obtained in other flight or ground simulation experiments, divided basically by the type of control system investigated. These reviews emphasize man-in-the-loop experimental or operational results rather than analytic predictions, and are confined primarily to programs which specifically addressed a decelerating IFR capability. Additional studies aimed at conceptual design or specific requirements will not be reviewed here, but are collected in Group 4 of the annotated bibliography for reference (Appendix). Also, the majority of the recent developments in FAA certification for helicopter IFR operations is not included, primarily because the certification is generally for CTOL-like approaches (constant speed, low glideslope angle) that do not specifically address the additional deceleration capabilities of helicopters.

3.2 Angular Rate Augmentation Control Systems

The first group of investigations to be reviewed consists of those which considered no more than rate damping augmentation in pitch and roll, corresponding generally to the least complex system implemented in the X-22A study. Therefore, the following investigations may be considered as a group:

- PIFAX-H (References 4-9)
- JANAIR (References 10-14)
- VALT (Reference 15)
- CL-84 (References 16-19)
- X-22A Task IV (Reference 20)
- Operational Test (References 21-27)

Table 1 provides a summary of the programs, which are briefly reviewed below.

PIFAX-H was an Air Force program devoted to achieving an operational IFR capability for helicopters in the USAF inventory. Accordingly, the emphasis was on simple SAS changes and modified electromechanical displays. Through questionnaires sent to operational pilots regarding problems with their current displays, it was found that directional control assistance was required in addition to 3-axis control directors (Reference 4). The next step was a series of simulated IFR profiles that were flown with a TH-1 helicopter. The profiles were not specifically aimed at landing approach, but for this task it was found that the TH-1 flying qualities below 70 knots made IFR flight marginal, and again some stability augmentation plus 3-axis control directors were among the recommended improvements (Reference 5); the primary program recommendations therefore became: (1) development of yaw augmentation to provide both heading hold and turn following, and (2) 3-axis control directors plus improved ADI and HSI instruments (Reference 6).

An interim step was then taken of adding improved ADI, HSI, IVSI, airspeed, and altimeter instruments but without control directors; no improvement over the basic TH-1 instrument complement was found, and the pilots still wanted 3-axis control directors and improved stability (Reference 7). Yaw axis augmentation was then flight tested in the TH-1 (Reference 8). As implemented, the system provided heading hold from hover to top speed; above 30 knots, bank attitudes of more than 5° gave "turn following" (the operation of which is not described in the reference), with heading hold returning when the bank attitude returned to 2°, and less. The flight results were mixed, with no clear improvement shown.

TABLE 1.- PROGRAMS INVESTIGATING RATE AUGMENTATION CONTROL SYSTEMS

	Type of study and aircraft	Type of display	Type of approach	Major conclusions/recommendations for rate damping control system
PIFAX-H (4-9)*	Flight test (TH-1)	Electro-mechanical (ADI, HSI)	Inst. decel. to 70 kt	1) 3-axis control directors required 2) Additional yaw augmentation required 3) Satisfactory system attainable
JANAIR (10-14)	Ground simulation (UH-1)	Electronic head-down (Vertical or plane)	Inst. decel. from ~70 kt to hover	1) 3-axis control directors required 2) Satisfactory system attainable
VALT (15)	Flight test (CH-46)	Electro-mechanical (ADI, moving map)	Inst. decel. from 50 kt to hover	1) 3-axis control directors required 2) Satisfactory system not attainable
CL-84 (16-19)	Flight test (CL-84)	Electronic head-up	Inst. decel. from 90 kt to 45 kt (16). Inst. decel. from 40 kt to hover (17, 18)	1) Satisfactory system not attainable 2) Height control a major problem
X-22A (1, 20)	Flight test (VSS X-22)	Electronic head-down (1) head-up (20)	Inst. decel from 100 kt to hover (1). Inst. decel. from 65 kt to hover (20)	1) 3-axis control directors required for acceptable system (1). 2) Wind direction important factor
Operational test (21-27)	Flight test (UH-1, OH-6, OH-58, AH-1)	Electronic head down (23,24) head up (21) Electromechanical (22, 25-27)	Const. speed inst. 80 kt (21) 70-90 kt (23,24)	1) Good VFR flying qualities important 2) 3-axis control directors can be substantial help

*Numbers refer to references.

A subsequent flight test with the TH-1 examined the use of 2 or 3-axes control directors in combination with the refined displays of Reference 7 but without the yaw-axis augmentation of Reference 8 (Reference 9). Constant speed instrument approaches at 90 knots were flown on a 3° glideslope to the decision altitude; no instrument decelerations were performed. Although the constant speed approaches could be flown with either the three-cue or two-cue director, the workload was considered too high for single-pilot IFR operations, and a need for increased aircraft stability was emphasized.

It was not possible to find documentation of any final phase of PIFAX-H in which both the yaw axis augmentation and 3-axis flight directors were implemented and investigated in flight, and hence the efficacy of this combination in providing an IFR capability for this type of helicopter cannot be determined. The X-22A (Reference 1) results plus those to be discussed shortly, however, tend to indicate that decelerating approaches on instruments using the PIFAX configuration would probably not have been possible with satisfactory pilot performance and workload. Of value from the program, however, are the following observations taken from References 4 and 7:

- For single rotor helicopters, vertical-directional axes coupling is a problem when flying on instruments. The TH-1 use of separated course, turn and slip indicators does not provide the necessary information adequately.

- Valid omnidirectional airspeed information below 40 knots is needed. Groundspeed is also desired.

- With simple rate SAS, control directors are required, even if some directional assistance beyond rate damping is given (assuming TH-1 dynamic characteristics).

- Pilots want knowledge of tip-path-plane position for articulated rotors (single-rotor-helicopters) because of control lag.

A series of studies and ground simulation experiments performed by Honeywell under JANAIR sponsorship also emphasized rate damping stability augmentation. These studies were aimed directly at steep decelerating approaches on instruments, generally using the UH-1H as the study vehicle. In the first study, a set of information requirements was developed based on pilot questionnaires, and electromechanical or electronic formats were then designed to present these data; the required data were determined to be: pitch and roll attitude, vertical and lateral flight path error, vertical velocity, groundspeed, radar altitude, heading, range, bearing, longitudinal and lateral position error (Reference 10). In addition, 3-axis control directors were determined to be necessary. Four "formats" were investigated: separated electromechanical, integrated electronic vertical (IEVD), and plan position (horizontal) electronic (PPI) presented in two reference frames. The aircraft had rate damping in pitch, roll, and yaw, and the task consisted of either straight or parabolic descents at different angles, with a deceleration from 70 knots to hover on instruments during the descent. No significant difference among the display formats for approach profiles was found, although a trend to increasing performance errors with increasingly steep approaches was seen with the UH-1H.

A following study investigated the IEVD and PPI displays in combination with stability/control augmentation consisting of:

(1) Rate SAS in all three axes again

(2) Rate SAS plus heading hold

(3) Attitude command in pitch and roll

(4) Attitude command plus heading hold

In general, performance (tracking error) was not considered improved, and the main effect noted was decreased control activity (Reference 11). It is important to note, however, that no wind, and a low level of

turbulence, were used in this phase. The influence of wind/turbulence was examined separately in the next study (Reference 12), but only with the rate damping SAS. With winds, approaches on the steeper glideslope (15°) investigated were noticeably worse than the shallower (6°) one, and in fact "high" (20 knots) winds and concomitant turbulence led to a statistically significant number of losses of control.

The results of the three studies were summarized in Reference 13 and used to recommend a configuration for flight investigation. The information requirements noted previously used were included along with 3-axis control directors, but it was felt that electromechanical instruments would be suitable. Rate damping in all three axes was deemed sufficient, although heading hold was considered desirable. Reference 14 turned these recommendations into specifications for electromechanical ADI and HSI instruments, and detailed a flight test plan for a flight experiment to be conducted by the Army (ECOM) using a UH-1H. No documentation of this flight test program was found.

On the basis of the ground simulation experiments conducted in these JANAIR studies, we may note the following items:

- The JANAIR and PIFAX-H programs both resulted in similar control-display configuration recommendations for UH-1 class helicopters: rate damping pitch and roll, rate damping yaw with perhaps turn-following and/or heading hold, three-axis control directors with electromechanical instruments. The X-22A Task III (Reference 1) results indicate that such a combination would be unsatisfactory for instrument decelerations to hover.

- Although attitude augmented control systems were examined in the JANAIR program, it was concluded that this level of augmentation was not required, again in contrast to the Task III X-22A results. However, the efficacy of this type of augmentation in regulating higher wind/turbulence levels was not investigated.

- The JANAIR investigation of winds/turbulence showed no effect of wind direction on task performance. This result is different also from Reference 1, in which crosswinds were found to degrade pilot ratings considerably for rate-augmented configurations.

- The information requirements determined in the JANAIR programs include ground velocity data and corroborate the X-22A results.

- JANAIR approach tasks used constant deceleration levels between 45 and 70 knots for a variety of approach angles, and found such profiles reasonable on instruments.

The usefulness of the JANAIR and PIFAX-H recommended configurations is brought into some question by flight results obtained in the VALT program conducted by NASA. Initial configurations examined in the VALT experiments used high gain attitude command control systems, and these results will be reviewed later; follow-on work, however, compared the earlier control system with a simpler attitude SAS and also with rate-damping augmentation (Reference 15). The helicopter used in these flight tests was a CH-46; the task was completely instrument approaches along a 6 degree glideslope employing a constant attitude deceleration from 50 knots to hover. The primary displays were an electromechanical ADI with three-axis control directors plus an electromechanical moving-map horizontal situation display, as in earlier VALT work. Two information levels were examined: raw glideslope on the cross-pointers, and 3-axis control directors. Both the rate damping and simple attitude SAS used directional lateral acceleration feedback in addition to directional rate damping.

It was found in flight tests that it was possible to perform the task with the rate damping control system in combination with the control directors, but at an unacceptably high level of pilot workload (Pilot Rating = 7). Part of the reason for this result was attributed to the fact that the CH-46 had an unstable real root with rate damping only, so that attitude control was difficult in any long-term sense.

Comparing this VALT result with the JANAIR and PIFAX-H studies as well as the X-22A Task III experiment, the following points are evident:

1. The efficacy of rate damping stability augmentation depends highly on the unaugmented vehicle characteristics. Control director information appears to be necessary with this type of control system to achieve even adequate performance during descending decelerating approaches.

2. It may be inferred from all four programs that directional augmentation above basic rate damping (e.g. sideslip control and/or heading hold assistance) is probably required for the low speed and hover parts of the instrument task.

Two display formats that did not explicitly include control directors were examined in combination with a rate damping* control system during the CL-84 tripartite experiments (References 16, 17, 18). These experiments, however, like the Task III X-22A experiment, used the enhanced versatility of electronic instruments to integrate more information into the primary display; in addition, the formats were shown head-up.

In the first phase (Reference 16), the instrument approach task was a 4° glideslope of 90 knots followed by a level-off, with deceleration starting after the level off; breakout to visual reference occurred at about 45 knots, half-way through the constant deceleration. Although the CL-84 is a tilt wing, no independent thrust vector rotation command was given, nor were 3-axis control directors; the format did, however, integrate horizontal and vertical raw position data by showing glideslope brackets and a moving landing pad, and also included horizontal translational ground velocity in a "guidance vector" command presentation. Among the results noted were extreme difficulty in tracking airspeed and altitude during the deceleration, a need for additional pitch and roll stabilization, and the benefits of the inherent high weathercock stability of the CL-84 for sideslip control on instruments.

* The CL-84 has a small amount of pitch attitude damping also, but it is low enough to amount to essentially pitch rate only (Reference 3).

The Phase II experiment (References 17, 18) emphasized an electronic head-up display format based on the ubiquitous "desirability" of one-to-one overlays with the real world; the format was based to a large extent on concepts described in Reference 19, and featured a perspective runway symbol intended to overlay the actual runway, plus a glide-slope command bar and speed error information. For this experiment, the instrument task consisted of constant 40 knots approaches at 6 to 12 degrees followed by a level-off and then an essentially exponential deceleration to hover on instruments. Among the conclusions were that control directors (particularly for thrust magnitude) are required for deceleration, the workload during deceleration was unacceptably high, improved presentation of pitch and altitude was required, and the usefulness of the runway overlay was obviated for crab angles over 10°.

Comparing the CL-84 results with the previously discussed programs, we find:

- A rate damping control system without control directors results in unacceptably high workload for the VTOL approach profiles considered in Reference 1, 16-18. The VALT, X-22A, and CL-84 results from flight test indicate a need for control directors even if integrated electronic display formats are used.

- Careful attention to the type of information presented and the method in which it is shown is required when electronic instruments are used.

Rate damping augmentation in combination with several levels of head-up displayed information was also investigated in the Task IV X-22A flight experiment (Reference 20). In this case, aerodynamic characteristics representative of the AV-8B Advanced Harrier were simulated during instrument approaches; the task consisted of initial approach at 65 knots, acquisition of a 5° glideslope, and a constant attitude "one-step" nozzle rotation resulting in an exponential deceleration. Information levels included two and three axis control directors with and without explicit analog velocity and position presentations plus

velocity/position information without control directors. The rate system consisted of pitch, roll, and washed-out yaw feedback plus a very small amount of lateral-acceleration feedback and an aileron-rudder interconnect.

Results from this experiment contradict to some extent those of the previous X-22A flight program as well as the CL-84 and VALT findings:

- The rate SAS control system in combination with velocity command formats was given some ratings of "satisfactory" (PR < 3 1/2) for the full instrument approach; the need for control directors was not as apparent as in the Reference 1 experiment. It should be noted, however, that the data scatter for this combination was very large, and some ratings of unacceptable (PR > 6 1/2) were also obtained, indicating the sensitivity of the combination to factors such as wind/turbulence.

- The inclusion of control directors for the rate SAS system did not appreciably improve the pilot ratings.

- All control system configurations included a heading-hold mode for hover, which may have helped improve the rate SAS ratings for instrument hover relative to the Reference 1 experiment.

Many operationally-oriented programs attempting to develop an IFR capability for existing helicopters start with aircraft having rate-damping augmentation, and have also emphasized only display improvements. A series of investigations conducted by the Army ECOM laboratory, for example, was aimed at flight testing "off-the-shelf" display additions to a UH-1 helicopter (References 21, 22). In Reference 21, the display was a Sundstrand HUD with runway (overlay) symbol, flight path angle, and flight path bar; this display was flown visually and compared to simulated (under the hood) IFR approaches using conventional instrumentation. Constant speed approaches along 6° and 9° glideslopes were flown; the speed isn't given in Reference 21, but appears to have been approximately 80-90 knots. The authors claim that the HUD

would "drastically" reduce workload with more information on it, although no data supported the claim. The data showed difficulty with using the HUD in crosswinds, and aircraft stability problems may have been evidenced by the fact that performance was worse for the 9° glideslope.

Reference 22 is another flight test, from the same ECOM group, using the UH-1 helicopter and four commercially-available 3-cue flight director display systems*. In this case it is unclear from the reference what the approach speeds were or whether a deceleration was used. The results imply that the control directors in all three axes were too sensitive and successful decelerated approaches were not possible with any of the systems.

Flight tests with similar intents of obtaining an "off-the-shelf" IFR capability for existing helicopters have also been conducted by the Army ASTA (now AEFA) with several helicopters. References 23 and 24 were instrument flight evaluations of the OH-6 with "basic" IFR instrumentation (the OH-6 instruments plus an IVSI and a turn-and-slip indicator) and an electronic ADI with 3-axis control directors. Poor force and trim characteristics of OH-6A made it unacceptable for IFR with the basic instruments. The initial tests with the 3-axis directors improved it to acceptable but unsatisfactory because of director command sensitivity (Reference 23); a further series of tests with improved sensitivities demonstrated satisfactory (PR=3) ILS approaches including a programmed deceleration to 40 knots from 70-90 knots.

In Reference 25, the OH-58A was examined with the "basic" package (OH-58A instruments plus IVSI) and with an electromechanical ADI incorporating a 2-axis control director. Again, the basic instruments proved unacceptable because of high pilot workload due to poor control centering and inadequate lateral-directional damping characteristics. The control

* One of these systems appears to be the one built for the JANAIR studies as defined in Reference 14. The author was unable to locate a document describing the flight test results of this unit in that context, however.

directors were based on a "frontside" power operation philosophy, with pitch commands to follow altitude; pilots could not perform ILS approaches satisfactorily using these control directors, although workload was reduced for other task elements such as cruise. It was shown in Reference 26 that adding to the OH-58A a SAS which provided rate-command-attitude-hold characteristics in pitch, roll, and yaw significantly improved the flying qualities, but the possible advantages for IFR flight were not examined. An examination of the AH-1G IFR capability in Reference 27 is interesting in this context, because the aircraft with rate SAS in pitch, roll, and yaw exhibited excellent VFR flying qualities; in fact, the authors claim measured precision-workload indices were five times better than with the OH-6A. In this case, constant speed 3° ILS approaches could be performed satisfactorily (PR $<$ 3 1/2) using the basic instrument complement.

If we consider all of the work which examined rate damping control systems for helicopter/VTOL instrument approach together (References 1, 3-27), the following inferences can be drawn:

1. It is clear that the suitability of this type of augmentation is highly dependent on the unaugmented vehicle characteristics and the approach task. Further, the sensitivity to external disturbances (wind/turbulence) is very high. Only three flight tests demonstrated satisfactory (in the sense of Cooper-Harper pilot rating better than 3 1/2) IFR approach capability: References 20 (X-22A Task IV), 24 (OH-6A with electronic flight director), and 27 (AH-1G). Of these three, the AH-1G demonstration was for essentially a fixed-wing approach profile (3°, 100 knots constant speed), and the X-22A results also demonstrated an unsatisfactory capability if winds/turbulence were present. The OH-6A handling characteristics that precluded acceptable IFR approaches without the electronic flight director were predominantly low frequency problems (force gradients, poor trimmability) rather than dynamic deficiencies (e.g. low lateral-directional damping as in the OH-58A); even though judged satisfactory with the three axis control directors in this context, it was noted that pilot workload was still high.

2. If decelerating approaches are to be performed on instruments with rate-damping-type control systems, 3-axis control directors are a requirement to approach satisfactory performance. The Task IV X-22A results (Reference 20) appear to contradict this inference to some extent, but it is important to note that the deceleration was accomplished primarily by the simulated nozzle rotation, with attitude held constant: no attitude command to perform the deceleration was required. While apparently acceptable performance was obtained with both head-up display formats investigated on the CL-84, neither of which included 3-axis control directors, both programs noted pitch attitude and height control problems.

3. The directional axis augmentation appears to require particular attention. Turn-following capability (to regulate sideslip) during the approach is important. The CL-84 had this characteristic intrinsically, and Reference 16 notes that it was added to the SC-1 through augmentation; the Task III X-22A (Reference 3) results implied that one problem with the rate-damping control system was lack of weathercocking stability; helicopter instrument panels are frequently considered deficient in presenting this information (References 4, 10, 23, 25). Heading-hold for the hover appears desirable in principle (References 3, 6), although the blended implementation approach taken in the PIFAX-H program does not appear to be suitable (Reference 8).

4. The altitude-range and deceleration profile for helicopter decelerating instrument approaches should be tailored to the aircraft characteristics. The steepness of the approach is restricted by vortex-ring or autorotation considerations; a minimum period of time in the "dead-man's zone" for single-engine machines is required. The constant attitude deceleration used in References 15 and 24 appears to be best from a pilot workload point of view on the basis of the results summarized so far.

5. The primary advantage of rate augmentation systems is the simplicity of the implementation (rate gyros essentially the only required sensors) and the compatibility with limited-authority series servo

installations (essentially zero steady-state feedback). This simplicity must be balanced against the fairly complex on-board processing required to drive the control directors, and the concomitant high workload for the pilot. A minimal combination appears to include 3-axis control directors plus directional sideslip/heading augmentation as was hypothesized in the PIFAX-H program (Reference 6).

3.3 Attitude Augmentation/Command Control Systems

The advantages of control systems that include feedback of pitch and roll attitude include:

- Stabilization of the oscillatory roots that are typical in hover.
- Reduction of the influence on the aircraft angular motions caused by external disturbances such as turbulence.
- Reduction of cross-coupling responses due to control inputs.
- When implemented as attitude command by the stick, feedback to the pilot of some pitch and roll attitude information through the control stick forces.

Programs that have emphasized or included this type of augmentation are (Table 2):

- X-22A (References 1, 20)
- VALT (References 15, 28, 29, 30)
- ITED (References 31-34)
- NASA CH-53 and SH-3 (References 35, 36)
- Operational Test (References 37-42, 26)
- HOVVAC (References 43-45)

Although these programs have been grouped together for convenience, it is important to note that some differences in the implementations

TABLE 2.- PROGRAMS INVESTIGATING ATTITUDE AUGMENTATION/COMMAND CONTROL SYSTEMS

	Type of study and aircraft	Type of display	Type of approach	Major conclusions/recommendations for attitude augmentation/command control system
X-22 (1, 20)*	Flight test (VSS X22)	Electronic head down (1) head up (20)	Inst. decel. from 100 kt to hover (1). Inst. decel. from 65 kt to hover (20)	1) Satisfactory system attainable 2) Pitch/roll control directors not required 3) Velocity status/command required
VALT (15, 28-30)	Flight test (CH-46)	Electromechanical (ADI, moving map)	Inst. decel. from ~50 kt to hover	1) Satisfactory system attainable 2) Pitch/roll control directors required (when translational velocity not given explicitly)
ITED (31-34)	Ground simulation (CH-53)	Electronic head down	Inst. hover	1) Satisfactory system attainable 2) Velocity status required
NASA CH-53 and SH-3 (35, 36)	Flight test (CH-53, SH-3A)	Electromechanical (35) plus TV (36)	Const. spd. inst. (35). Inst. decel. from 80 kt to hover (36)	1) Conventional displays inadequate for decel (35) 2) Satisfactory system attainable with velocity status/command, no control directors (36)
Operational test (37-42, 26)	Flight test (S-61, CH-53, CH-54, UH-1)	Electromechanical (37, 40-45) Electronic head down (38, 39)	Const. spd. inst. (37, 38, 40) Inst. decel. to 40 kt (39) Inst. decel. to hover (42)	1) Control directors required for decel with conventional instrumentation
HOVVAC (43-45)	Flight test (UH-1)	Electromechanical	Const. spd. inst. (44). Inst. decel. to 40 kt (45)	1) Recommended display integrating status and command information

*Numbers refer to references.

exist. In several cases, forward loop integrators or switches in the feedback loops are used to provide a rate-command-attitude-hold response to control inputs; in general, this mechanization is emphasized for up-and-away flight, while attitude command is used for hover. Most of these control systems include heading hold, while a few include turn-following directional augmentation for forward flight. Many of the systems include altitude hold in the collective axis, but only a few augment the vertical velocity damping in addition (e.g. References 28, 30, 43). The following descriptions of these programs will point out these differences.

Both X-22A programs considered attitude augmented control systems in addition to the rate-damping control systems described earlier; in both programs, attitude command and rate-command-attitude-hold implementations were considered along with dual-mode yaw augmentation giving turn-following or heading hold functions. Recall from the previous descriptions that both programs examined decelerating approaches completely on instruments using integrated electronic display formats. In both cases, attitude command augmentation with the dual-mode directional system showed enhanced mission suitability relative to the rate-damping control system: the pilot ratings were better for equivalent display levels, less control director information was required (Reference 1), and considerably less sensitivity to winds/turbulence was evident. In Reference 1, a rate-command-attitude-hold implementation was found less satisfactory than attitude command, although little difference between the two types was observed in Reference 20. In general, pitch and roll stick control directors were not required for pilot ratings of satisfactory if attitude command augmentation and integrated analog position and velocity data were presented on the display.

Several experiments conducted under the aegis of the VALT program, including the one described previously (Reference 15), have concentrated on attitude command augmentation. In Reference 28, a ground simulation of the CH-46 was conducted for an approach task consisting of a 6° approach at constant 42 knot speed, level off, and a constant deceleration to 10 knots. The primary display was an electromechanical ADI with 3-axis control directors (no moving map); both control director and raw

deviation information levels were considered in the experiment. Three control systems were evaluated:

- pitch/roll attitude command, dual-mode yaw
- above plus vertical damping augmentation with altitude hold
- longitudinal velocity commanded by pitch stick, course by lateral stick, vertical and directional as in second system

In this experiment, it was found that vertical augmentation plus the attitude command augmentation was required in combination with 3-axis control directors to achieve an acceptable system.

The first series of VALT flight experiments using a CH-46 helicopter is discussed in Reference 29. In spite of the Reference 28 results, the sole control system examined was a model-following variant of attitude command in pitch and roll, and a dual-mode system in yaw which provided either turn-following or heading-hold; no vertical augmentation was considered. As discussed earlier, primary displays were a 3-axis flight director (pitch, roll, thrust) superimposed on the ADI and an electromechanical moving map which presented horizontal position and heading information; no explicit display of translational velocities was provided. The experiment consisted of approaches along a steep glide path (6 degrees or 15 degrees) employing a deceleration from 45 knots to hover, followed by a vertical let down, all on instruments.

A part of the experiment was devoted to ascertaining a suitable deceleration profile for helicopter instrument appproach. An exponential velocity-range relationship was found to lead to poor initial tracking and an excessive period of time being spent at low speeds, while a constant level of deceleration was found to result in increasing nose-high attitudes near the hover, which the pilots did not like; the authors concluded that, for helicopters, the best task performance was achieved with a constant attitude deceleration.

A major conclusion from the Reference 29 experiment was that, although good approach tracking performance was obtained with the control-display combination investigated, the attendant pilot workload was operationally unacceptable, and that a display which provided integrated status and command information was required. It is interesting to note that, in the later Reference 15 experiment, this control-display combination was rated as satisfactory. Two reasons may be hypothesized for this improvement:

(1) The Reference 15 task did not include vertical letdown, whereas the Reference 29 task did. The importance of integrated velocity information would be highest for eliminating drift at touchdown.

(2) Small changes in control-director logic philosophy occurred between the two experiments. In the first (Reference 29), attitude rates were included in the director laws, whereas they were not in the second (Reference 15).

The most recent VALT flight experiment added vertical velocity augmentation to the Reference 29 control-display combination (Reference 30), thereby looking at the second ground-simulated control system of Reference 28 in flight. Approaches at 10° were flown, starting at 65 knots and using a constant attitude deceleration to hover. Although satisfactory performance had been obtained without the vertical augmentation, it was found that a definite improvement in glideslope tracking was obtained with it.

Comparing all the VALT experiments (References 15, 28-30) with the X-22A experiments (Reference 1, 20), the following points may be made:

- While rate-damping augmentation was at best marginally satisfactory, and generally unacceptable, attitude command augmentation in pitch and roll provided a satisfactory system for descending instrument deceleration given appropriate displayed information.

- As was noted earlier, directional augmentation to aid turn-following and provide heading hold when requested appears very important. Reference 3 demonstrates the efficacy of the Reference 1 dual-mode system in improving crosswind performance, and pilot ratings in the Reference 1 experiment were essentially unaffected by cross-winds when the dual-mode system was included.

- The required level of display information sophistication with an attitude command control system appears at first glance to be inconsistent between the X-22A and VALT experiments. Ratings of satisfactory were obtained in both X-22A experiments without pitch/roll stick directors, whereas the VALT experiments all included 3-axis directors. The VALT displays, however, did not display explicitly translational velocity status and command information as did the formats found satisfactory in the X-22A experiment; one configuration in Reference 1 selected to be comparable to the separated information presentation of VALT was in fact found unacceptable because of the lack of velocity data.

- No clear preference between attitude command and rate-command-attitude-hold implementations was found in Reference 20, although in Reference 1 it appeared that control directors would be required with the rate command version. This question was not addressed in the VALT experiments. To some extent, it is a moot point, since the sensor requirements are equivalent; for systems using limited authority series servos, however, the rate-command implementation might be preferable, and hence the relative desirability needs to be ascertained.

As in the VALT experiment, the majority of work investigating helicopter instrument approach and hover has used pitch and roll attitude command as a baseline. An example is a series of programs conducted by ECOM to develop electronic formats (ITED) suitable for superimposition on a FLIR CRT picture of the outside world (References 31-34). The first three developmental studies used ground simulations of the CH-53 as the baseline vehicle. In Reference 31, the control system included attitude

command in pitch and roll, plus heading hold and altitude hold (without vertical rate augmentation). The task was primarily precision hover, without a descending prescribed deceleration. Among the results obtained in defining the format was that explicit display of horizontal translational velocities was essential for accurate hover even when the display was superimposed on a video image.

The next investigation in the series (Reference 32) again used the CH-53; some flights were performed with only the pitch/roll attitude command (no heading or altitude hold), while the remainder had the full system. Ten "formats" (including with and without a video image) were investigated, none of which included control directors. The task for this experiment was again essentially precision hover, although it included an acceleration and deceleration (open-loop) from an initial hover point at 500 feet range. Among the results obtained from the ground simulation were:

- The heading hold and altitude hold features were required for accurate hover regardless of display.
- The electromechanical ADI was required in addition to the video image and superimposed format (the electronic format had attitude information only on the periphery).
- Both ground-referenced position and velocity information were required for accurate hover.
- Comparable accuracies were achieved with the full-information format with and without the video picture of the outside world.

A follow-on investigation, again a ground simulation of the CH-53, used the full format from Reference 32 plus horizontal translational acceleration status information. In this case, three control variations were examined:

- Rate-damping in pitch and roll plus altitude and heading hold features of previous system.

- Attitude command in pitch and roll plus altitude and heading hold (the previous system).

- Quasi-velocity command in pitch and roll (i.e., feedback of u and v to pitch and roll respectively) plus altitude and heading hold.

No display variables other than scalings were considered; the electronic format was superimposed on a video image of the outside world. A task similar to the earlier investigations was used: initiate in hover at 100 feet AGL, 300 feet range, fly to hover at 50 feet AGL over landing zone. It was found that:

- The rate-damping control system could be stabilized with the addition of translational acceleration data (which was more or less equivalent to a sensitive display of aircraft attitude at hover -- i.e., $\dot{u} \cong -g\theta$, $\dot{v} \cong g\phi$). This system resulted in worse hover performance than the others and required more pilot training, however.

- The attitude command and velocity augmented control systems were approximately the same in performance.

Reference 34 uses the results of these three studies to propose electronic formats for superimposition on a FLIR video image in AAH-class helicopters. No simulation results are reported, although the formats will be investigated in a simulation of the YAH-64 performing bob-up maneuvers to be conducted at NASA-ARC in December 1978. The influence of the attitude command control system used in the CH-53 investigations can be noted in the <u>absence of attitude information</u> on these Reference 34 formats for transition/NOE/hover.

If the ITED investigations are compared with the X-22A and VALT studies, the following points can be made:

- Explicit display of horizontal translational velocities, probably in analog form, is required for accurate instrument hover.

- Control directors are not required with an attitude command control system for instrument hover or approach if integrated electronic displays are used.

- The addition of translational horizontal velocity augmentation may give limited performance increases, given a certain level of displayed information.

- The addition of a video scene of the real world -- and, by extension, of a breakout to visual with a HUD -- may not significantly improve the performance of an attitude-augmented aircraft with proper format information.

The CH-53 helicopter and associated attitude command, heading and altitude hold control system, has been used in flight tests conducted by NASA also. Reference 35 summarizes several flight tests aimed at differing aspects of civil helicopter applications, one of which was IFR operations. Using the basic CH-53 electromechanical instruments (apparently), approaches from 60 knots with a deceleration to 20-30 knots were examined with three levels of control augmentation:

- Pitch/roll attitude command, heading hold, altitude hold

- Pitch/roll attitude command, no heading or altitude hold

- No SAS

The task could be performed satisfactorily with the full SAS but not with no SAS; a full deceleration to hover was impossible with the full SAS, however, given the basic instrument complement.

A separate NASA investigation, including both ground simulation and flight test with the SH-3A, is documented in Reference 36. The control system consisted of the pitch/roll attitude command plus heading hold like the CH-53, but altitude hold was not used since descending decelerating approaches were considered. An intriguing display concept was examined. It consisted of a CRT with visual scene of outside world

(closed-circuit TV used to simulate FLIR for example) with no electronic overlay or superimposed symbology; directly below the CRT were five electromechanical tape instruments showing: (lateral) cross-range error, rate-of-climb error, altitude, range, and groundspeed. The latter three were absolute status data but with scales arranged so that range served as a command for altitude and speed. In this case, the task was a descending (6° glideslope) decelerating approach (essentially constant attitude) from 80 knots, 800 feet AGL to hover at 40 feet AGL. It was found that the displays significantly reduced workload and enhanced repeatability compared to the video image alone.

These two programs serve to reinforce or amplify some of the observations made from the X-22A, VALT, and ITED programs:

- Conventional instrumentation alone is not sufficient for decelerating instrument approaches to hover; with attitude command augmentation, however, constant speed approaches are possible.

- If one considers the video image of Reference 36 as a "perfect" contact analog position situation display, then additional status and command information is required to reduce pilot workload during decelerating descents even with attitude command augmentation.

A variety of operationally-oriented programs has also either used aircraft that come equipped with attitude command augmentation or has investigated add-ons that provide this type of control system. For example, North Sea oil rig operations by KLM Noordzee Helikopter require an IFR capability (Reference 37). The S-61 helicopters that are used provide attitude command in pitch and roll plus heading hold. Electromechanical instruments are used, but the ADI is an expanded unit (6 inches), the instruments are grouped closely together, and altitude/rate-of-descent instruments are moved to the left of the ADI. With this combination, constant speed approaches at 70 knots can be performed. In Reference 38, the electromechanical ADI was replaced with an electronic display incorporating a 3-axis control director, which was

then flown operationally. Although constant speed approaches at 70 knots were still flown, it was felt that the addition of control directors would permit slower speeds with enhanced safety in the event of an AFCS failure.

An operational examination of an electronic format superimposed on a FLIR picture was conducted using a CH-53 in Reference 39. Again, the aircraft control system included attitude command in pitch and roll plus heading and altitude hold (presumably -- the reference does not so state). The electronic format includes 3-axis control directors in a somewhat different form than the displays by the same manufacturer evaluated in References 24 and 38. Approach angles of 3, 6, 9, and 12 degrees were flown successfully to 150 feet AGL at 40 knots and 300 fpm; the deceleration was programmed as a function of altitude but is not described, nor is the initial velocity.

References 40 and 41 examined the IFR suitability of two helicopters equipped with rate-command-attitude-hold control systems. In Reference 40, the aircraft was a CH-54B equipped with rate-command-attitude-hold in pitch and roll, heading hold, and altitude hold. The instrumentation was conventional electromechanical. Although instrument approaches were not performed, simulated instrument operations were conducted in hover, climb, and cruise; it was reported that the excellent controllability of the helicopter would make it suitable for IFR missions. Reference 41 examined a UH-1N with add-on AFCS plus a hover coupler. The AFCS provided rate-command-attitude-hold in pitch and roll plus heading hold; the displays were conventional electromechanical. It was found that the AFCS significantly improved the flying qualities over the basic aircraft, and the heading hold in particular enhanced the IFR capability; essentially neutral speed stability at 90-110 knots and the lack of turn-following augmentation were deficiencies which would hinder IFR operations, however. No specific investigations of approaches on instruments were performed.

In Reference 42, an add-on system which augmented both controls and displays was investigated in flight, using a UH-1N helicopter. The

system added 4-axis (rudder also) control directors on electromechanical ADI and HSI instruments, as well as integrated raw glideslope deviation, radar altitude (analog rising pad) and turn/slip information on the ADI. Although the reference is not too clear on this point, the system also apparently provides attitude command augmentation in pitch and roll for manual approaches. Decelerating approaches from 80 knots to hover were performed on a 6° glideslope, and satisfactory performance was claimed.

A final program which included design, construction, and flight test of a control system aimed at providing an instrument approach capability is the HOVVAC program (Reference 43-45). The final system provided, for hover, attitude command in pitch and roll, directional rate damping only, and vertical velocity augmentation. It was found in the design process that this system required at least 50% authority for the series servos -- a drawback of high gain attitude command systems. The control system switches to rate-command-attitude-hold in pitch/roll, directional turn-following, and no vertical augmentation at a speed between 50-60 knots; this velocity was picked on the basis of the change from "backside" to "frontside" operation (Reference 43).

Although no documents specifically describing manual approaches with the HOVVAC system were located, References 44 and 45 describe flight trials in a UH-1H equipped with the HOVVAC control system that investigated coupled (automatic) approaches; outer-loop guidance loops were fed into the HOVVAC computers to achieve this capability. In Reference 44, constant speed approaches on curved (in azimuth) paths with 3° glideslope were examined; problems were encountered with HOVVAC software, but apparently such approaches could be performed satisfactorily.

Reference 45 describes follow-on flight work to investigate coupled approaches against prototype MLS equipment using the UH-1N helicopter equipped with HOVVAC. Part of this program was to "debug" the HOVVAC for manual approaches, but the hover portion of the control laws could not be checked out within the constraints of the program. As a result, manual approaches were flown on glideslopes up to 9°, starting at 100

knots and using a constant deceleration (2 feet/second^2) down to 40 knots at 50 feet AGL. The display was an electromechanical ADI with three pointers driven by status information: the center needles had raw glideslope and localizer error data, while the left-side pointer showed airspeed error. While these manual approaches could be conducted successfully using this control/display combination, it was recommended that a display incorporating both situation and command information should be investigated, and tests should be conducted to determine the "optimum" cockpit display and IFR minimums.

If we consider all of the programs which investigated attitude augmentation control systems (Reference 1, 15, 20, 26, 28-45), and compare, on a general basis, their results with those discussed earlier for the rate-damping systems, the following inferences may be drawn:

1. Depending to some extent on the level of augmentation used, control systems that use feedback of pitch and roll attitudes tend to mask inherent vehicle characteristics by stabilizing oscillatory roots. The resulting control characteristics appear to be more generally suitable for decelerating instrument approach than those obtained using rate-damping feedback alone; in contrast to the very few satisfactory ratings obtained with rate-damping control systems as discussed in the last subsection, ratings of 3 1/2 or better were obtained in X-22A (References 1, 20), VALT (References 15, 30), ITED (Reference 33), and NASA SH-3 (Reference 36) programs for approaches that include instrument hover.

2. Levels of attitude augmentation that were examined range from natural frequencies of approximately 1.0 rad/sec (Reference 20) up to 4.0 rad/sec (References 1, 43). The lower value requires attitude feedback in the range of 2 to 5 equivalent stick inches per radian, while the higher value would require 32 to 60 inches/radian typically. It was found in Reference 43 that at least 50% series servo authority would be required in a UH-1 for the 4.0 rad/sec system, and in fact the high-gain attitude command systems used in References 1, 15, and 29 had 100% authority; a 1.0 rad/sec attitude command system was found in Reference 20 to provide mar-

ginally satisfactory control characteristics while still being compatible with 20% authority limits, however, and so it is unlikely that the high values are really required.

3. While rate-damping systems require 3-axis control directors to approach satisfactory performance, attitude command control systems have been shown to be satisfactory with less control director information (References 1, 20, 33, 36). It does appear, however, that integrated-information (i.e., electronic) display mediums are still required (References 1, 29). With an attitude command control system, apparently satisfactory performance has been obtained with displays ranging from 4-axis directors (Reference 42) to velocity status and command (References 1, 20, 33); this type of control augmentation therefore appears to offer some display flexibility.

4. Essentially all of the programs using attitude feedbacks include heading hold augmentation (References 1, 15, 20, 26, 28-42); the sole exception was the HOVVAC program, which included only rate damping directionally for hover. As was discussed in the previous subsection, directional augmentation appears particularly important at low speed and hover, and the inclusion of heading hold with the attitude command systems likely adds to their efficacy. Turn-following augmentation for forward flight was not as universally used (References 1, 15, 20, 28-30, 43-45), but, as was mentioned earlier, appears desirable.

5. Rate-command-attitude-hold and attitude command implementation require the same sensors, and no definitive preference between the two implementations is apparent in most of the references. In Reference 1, it appeared that control directors would be required with the rate-command implementation at hover, but the Reference 20 results do not indicate a similar requirement. It is probable that the HOVVAC concept is the most reasonable, with a switch from rate-command to attitude-command initiated either as a function of speed or at the pilot's discretion.

6. Constant-level (References 1, 28, 42, 43, 45) or constant-attitude (References 15, 20, 29, 30, 36) decelerations are the two profiles most commonly used. Of the two, the constant attitude profile was found preferable in Reference 29, and is probably the "best" for helicopters from a pilot's workload standpoint.

3.4 Velocity Augmentation/Command Control Systems

Working outward through the pilot's control/command loop structure, the next loop -- and essentially the last one before position closures for fully automatic operation -- is augmentation of the translational velocities, either in the aircraft's axis system or partly in an earth-referenced frame. Since the drag and height damping (X_u and Z_w) of helicopters is typically fairly low at low speed, feedback of the translational velocities to the control effectors can provide increased bandwidth and/or stability, and it is for this reason, plus the provision for direct control of the translational velocities by the pilot, that this type of control augmentation has been considered.

It should be noted that augmentation of the vertical velocity component was included in the last VALT experiment (Reference 30), the earlier CH-46 ground simulation (Reference 28), and the HOVVAC hover control system (Reference 43) discussed in the last subsection. In the case of Reference 28, vertical velocity augmentation was required, in addition to the attitude command system, to perform the decelerating approach; although the flight experiments with the CH-46 indicated satisfactory performance without vertical velocity augmentation, it was found in Reference 30 that such augmentation gave significantly improved glide-slope tracking. As will be discussed at the end of this subsection, augmenting the vertical velocity in particular appears to improve IFR capability substantially.

Programs which have considered augmentation of one or two horizontal velocities plus the vertical velocity are (Table 3):

TABLE 3.- PROGRAMS INVESTIGATING VELOCITY AUGMENTATION/COMMAND CONTROL SYSTEMS

	Type of study and aircraft	Type of display	Type of approach	Major conclusions/recommendations for velocity augmentation/command control systems
TAGS (46, 47)*	Flight test (CH-47)	Electromechanical (ADI, moving map, velocity tapes)	Inst. decel. from 45 kt to hover	1) Satisfactory system attainable
NASA VTOL (48)	Ground simulation (Generic lift/cruise fan)	Electronic head down	Inst. decel. from 120 kt to hover	1) Satisfactory system attainable
X-22A (1)	Flight test (VSS X-22)	Electronic head down	Inst. decel. from 100 kt to hover	1) Satisfactory system attainable 2) Vertical tracking performance improved 3) Display information nuances effect reduced

*Numbers refer to references.

- X-22A Task III (Reference 1)
- TAGS (References 46, 47)
- NASA VTOL (Reference 48)
- Other (References 28, 33)

In the X-22A program, longitudinal and vertical velocity components were augmented for a velocity control system, in the TAGS and one NASA study all three velocity components were augmented, in the ITED investigation the two horizontal components were augmented, and in the Reference 28 CH-46 experiment longitudinal and vertical velocities were augmented.

The TAGS program consisted of the design, fabrication, and flight test of a complex stability and control augmentation system aimed at achieving decoupled control of the three translational velocities plus aircraft heading. The resulting system was triplex FBW and was implemented in a CH-47 helicopter, along with a 3-axis side-arm controller (SAC) which commanded longitudinal and lateral velocity plus turn rate (Reference 46). This latter point is important, because some of the control difficulties encountered in flight may be attributable to this controller. Longitudinally, fairly high feedbacks of pitch rate, pitch attitude, and blended airspeed/groundspeed were used in conjunction with a third order command prefilter; fore-aft translation of the SAC was the longitudinal velocity command, with no spring gradient (the SAC was implemented to provide a force-per-commanded-acceleration, essentially). Lateral angular movement of the SAC commanded lateral velocity, which was implemented through feedback of roll rate, roll attitude, and blended groundspeed/airspeed plus a first order command prefilter. For directional control, yaw rate and heading feedbacks and a second order command filter were used; twisting the SAC provided the command of heading rate. Vertically, an effective rate-command-altitude-hold with a time constant of approximately 1.4 seconds was achieved.

The initial TAGS flight tests described in Reference 46 did not specifically examine IFR suitability; control for visual maneuvering and precision hover was emphasized instead. The results showed excellent

vertical control, good suitability for steady or low frequency control precision, excellent turn coordination and heading hold but some difficulty with precision hover both longitudinally and laterally. Follow-on flight tests (Reference 47) did, however, specifically address instrument approach, using the same system with some modifications to the longitudinal SAC characteristics. The majority of the approaches were straight 6° or 10° glideslopes computed using onboard INS equipment, with an initial velocity of 45 knots for the 6° and of 30 knots for the 10° glideslopes, respectively, and included "open-loop" decelerations to hover initiated at approximately 500 feet range. Displays were (1) an electromechanical ADI with raw glideslope and localizer deviation data on cross-pointers; (2) three tape instruments showing actual and command longitudinal speed (right of ADI), actual and commanded lateral speed (below ADI), and actual and command vertical velocity (left of ADI); (3) distance-to-go tape; and (4) a moving map horizontal situation indicator. It was found that completely hooded approaches entirely to hover could be performed satisfactorily given this control-display combination; the vertical performance in particular was good.

Reference 48 reports on a ground simulation of a VTOL aircraft which had independent control of all six degrees of freedom; hence, a velocity command system could be implemented which was essentially independent of the aircraft's attitudes. Pitch was implemented as attitude command, roll as attitude command in hover, rate-command-attitude-hold above 30 knots, with an optional implementation that commanded lateral velocity through roll as in a helicopter, and yaw was implemented as rate-command-heading-hold for hover and either rate command or sideslip command in forward flight. Either longitudinal velocity or acceleration could be commanded through a left-hand thumb wheel or coolie-hat, lateral velocity was commanded through the left-hand coolie-hat, and vertical velocity was commanded through the position of the power lever.

The program examined instrument approaches from 120 knots to hover for both curved and straight approaches. For the straight approaches, a constant deceleration profile was used; the curved approaches required constant horizontal deceleration while holding rate of descent constant,

followed by constant vertical deceleration also. A head-down integrated horizontal-vertical electronic display was used, with a fairly complicated format showing -- for longitudinal (left side) and vertical (right side) velocities -- status, control director, and pilot-commanded quantities, a lateral stick director, a landing pad symbol for the last 500 feet, vertical-frame "inertial" flight path angle, pitch and roll attitudes, and digital readouts of altitude, range, lateral deviation, and acceleration.

Among the interesting results of this program are:

- The pilot preferred the translational rate command being implemented through attitude rather than separate thrust deflection control in hover. This perhaps surprising result was due to ride qualities considerations and the controller implementation in this experiment, and is probably not universally correct.

- Command of acceleration rather than velocity longitudinally was preferred for the decelerating approaches; this result was probably caused in part by the type of deceleration profiles examined.

- The pilot preferred to initiate a flare near the ground, and did not follow the commanded "straight-in" profile in this region.

- Pilot ratings of satisfactory (PR$\sim$3 1/2) were obtained for the complete instrument task.

Two of the programs previously reviewed also considered augmentation of the horizontal velocity components. In Reference 33, a system which included feedback of u and v with no vertical augmentation was compared to the attitude command system; the display was the superimposed ITED electronic format including horizontal translational acceleration information, and the aircraft simulated was a CH-53 performing precision hover. Interestingly, very little performance improvement over the attitude command system was observed. In Reference 28, a system which provided longitudinal velocity command with longitudinal stick and

course with lateral stick plus vertical velocity augmentation was compared to the two attitude command systems (recall that one attitude command system included vertical velocity augmentation); the task included a descending deceleration from 40 knots to 10 knots for a simulation of a CH-46 helicopter. The performance was significantly improved with the velocity command system, and in fact was approximately equal without flight directors to the attitude command system with flight directors.

Comparing these four programs plus the Reference 1 X-22A experiment with each other the following points can be made:

- Both the X-22A (Reference 1) and NASA VTOL (Reference 48) studies showed a surprising preference for horizontal velocity commands implemented through attitude rather than direct force effectors. From the point of view of helicopters, this result is salubrious, because independent force generators are not generally present. The TAGS flight tests, however, demonstrate that some problems with such an implementation exist (Reference 46); in particular, the pilot requires direct control of attitude at touchdown, and the TAGS mechanization had to be changed to provide this characteristic as soon as one wheel touched. It is not clear what impact a moving landing pad would have on the performance of such an implementation.

- Improved tracking performance, particularly vertically, is a major advantage of velocity command augmentation (References 1, 46).

- In the longitudinal axis, it is apparent that command of acceleration may be preferred for decelerating approaches, depending on the profile being used (Reference 48).

On a general basis, comparing the results obtained using velocity augmentation systems with those of the rate damping and attitude command control systems discussed earlier, the following inferences may be drawn:

1. For a given type of display, task performance on decelerating descending approaches is improved with a velocity augmentation control system (Reference 1, 28).

2. Pilot ratings of satisfactory (PR$<$3 1/2) for the decelerating descending instrument task were obtained in all the programs which experimentally investigated velocity-augmented control systems (References 1, 28, 47, 48).

3. It is clear that the reduced sensitivity of velocity command systems to displayed information nuances that is implied by Figure 1 (Reference 1) is substantiated by the other programs. Reference 48 used a complex status, command, and control director electronic format, Reference 47 used electromechanical status and command (but no control director) instruments, and Reference 28 considered both 3-axis control directors and raw glideslope, localizer, and speed error information on electromechanical instruments. It appears that the reduced sensitivity to displayed information is a primary advantage over rate-damping control systems and, to some extent, attitude command control systems.

4.0 SUMMARY HYPOTHESES

In this section, the material reviewed in the preceding section plus some more general design concepts will be used to suggest general characteristics required for helicopter descending decelerating instrument approach, to hypothesize configurations suitable for further investigation, and to point out areas that still require experimental study. The following subsections will consider approach profiles, control system characteristics, display characteristics, and suggested combinations, respectively.

4.1 Approach Profiles

Taking as given the desirability of exploiting in IFR operations the helicopter's capability to decelerate to zero speed, the definition of approach profiles implies both spatial geometry (position) and translational velocity considerations, as outlined previously. Consider

initially the position profile. The following recommendations may be made:

1. Straight (constant angle) glideslope segment(s)

Most of the helicopter programs reviewed have used this type of profile. Some VTOL investigations (References 48, 49), and one of the JANAIR experiments (Reference 10) have examined a parabolic profile (constant rate of descent and constant longitudinal deceleration) and found pilot reluctance to follow commands giving fairly high sink rates near the ground. In Reference 50, a large number of helicopter approaches performed under visual (VFR) conditions were compared, and it was found that the altitude profile typically included a straightline segment of between 6 1/2° and 12° for the majority of the descent.

2. Flare (level-off) segment

References 1 and 20 specifically included a level-off segment at 100 feet AGL for the final 800-1000 feet of range in the altitude profile; some experiments which did not include a commanded level-off demonstrated that pilots would initiate an uncommanded flare (e.g. Reference 48). In the visual approaches examined in Reference 50, it was found that the altitude profile typically becomes concave up at approximately 1000 feet range before hover.

3. Hover commanded at non-zero altitude

Reference 10 actually compared profiles ending at zero altitude, zero speed with those ending at altitude; the advantages of ending at non-zero altitude are obvious. The value of altitude selected should depend on "dead-man's" zone considerations for single engine helicopters, the extent of the flare level-off, and obstacle avoidance.

4. Glideslope angle

Glideslopes from 3° to 20°, depending on initial speed and control/display characteristics, were examined in the reference documents. As has been noted, the initial speed and vortex-ring considerations are important factors in determining the glideslope angle, and it is difficult to generalize to one specific value. If 1000 fpm descent rate is assumed to be a reasonable upper limit, then a 6° glideslope would permit acquisition speeds of 100 knots, while 7 1/2° would permit 80 knots. The visual profiles examined in Reference 50 varied from 6 1/2° to 12° for speeds from 50 to 100 knots of four helicopter types. A reasonable first guess would therefore be a glideslope angle of 7 1/2°, if only because it is representative and is similar to projected STOL angles.

5. Azimuth profile

Almost all the helicopter programs considered approaches that were straight in azimuth, although some coupled curved azimuth approaches were examined in Reference 45. It is possible that civil applications could benefit from curved approaches as suggested in Reference 51; research experiments would be required to determine if additional control/display requirements are thereby incurred.

6. Lateral position

For approaches to a fixed site, the hover should be directly over the landing pad. Shipboard operations, however, typically end in a hover beside the ship (e.g. Reference 52); for these operations, a lateral offset from the guidance system centerline would generally be required.

The selection of the position geometry for the approach profile implies some relationships among the velocity commands (e.g. constant longitudinal deceleration requires constant vertical deceleration on a straight-line segment); hence, specification of the longitudinal velocity profile essentially defines the vertical velocity profile for the

approach geometry discussed above, while the lateral (approach-course referenced) velocity profile is independent. Based on the literature, the following recommendatons may be made:

1. Initial airspeed

As was discussed above, the initial airspeed and the steepness of the glideslope angle are interrelated through considerations such as vortex ring states. Selection of a 7 1/2° angle implies initial airspeeds of 80 knots can be used to keep within a 1000 fpm descent rate; 100 knots would give approximately 1250 fpm in zero-wind conditions. The helicopter programs that were reviewed used initial approach speeds ranging from 30 knots (TAGS, Reference 47) through 45 knots (VALT, Reference 29), 70 knots (JANAIR) and to approximately 80 knots (NASA, Reference 36; operational test, References 23-27); VTOL programs have generally considered slightly higher speeds on the order of 100-120 knots (References 1, 48). An advantage of the lower speeds is that the approach will be flown entirely on the "backside" of the power curve, but the implication is that the approaches will take a long time at a high power setting. A value of 80 knots, as used by the Army flight test activity in operational suitability tests (References 23-27), appears to be a reasonable selection.

2. Airspeed/groundspeed commands

As is discussed in References 1 and 3, a basic problem which must be addressed for helicopter or VTOL decelerating approaches is the fact that the magnitude of the along-track wind velocity component can be a significant fraction of the commanded aircraft velocity and in fact becomes comparable as the hover point is approached. If the commanded aircraft velocity is ground referenced for the entire approach -- which is the procedure used in most of the experimental programs that were reviewed (e.g. References 9-19, 28-30, 36, 39, 41, 42, 45, 47, 48) -- then acquisition airspeed must vary from approach to approach depending on headwind/tailwind component, which complicates the pilot's task and may violate

airspeed/rate-of-descent boundaries. One solution to the problem, proposed in Reference 53, is to refer the approach path and deceleration profile to the air mass by using either ground or aircraft measured wind velocity information to compute the transformation from ground-referenced to air-referenced coordinates. This technique ensures that both the path and the deceleration are always the same with respect to the air. As a result, however, the ground track varies with different winds, which may cause safety-of-flight problems in the presence of obstacles. Furthermore, near the hover it is position and velocity with respect to the ground that must be controlled by the pilot, and the commands must therefore be ground-referenced at this point.

The desiderata for the horizontal-plane velocity commands may therefore be summarized as:

- Airspeed rather than ground velocity command during initial part of approach to permit the same initial conditions each time.

- Aircraft course or heading during acquisition that accounts for the along-track and cross-track wind components to assure capture of the desired ground approach course.

- Maintenance of an airspeed/rate-of-descent relationship that is within the aircraft's transition corridor.

- Smooth, undetectable change to command of ground velocities to avoid transients in displays or automatic control systems.

- Command of longitudinal and lateral ground velocity components during hover.

In References 1, 3, and 20, these desiderata were met by commanding airspeed and course during the pre-deceleration phase of the approach, and longitudinal and lateral (approach-course referenced)

ground velocities during the deceleration to hover; the switch in command logic was made in a particularly simple manner using a groundspeed error signal, and resulted in the deceleration commencing at different range-to-go values depending on the wind. Although this particular implementation may not be "optimum" (e.g. perhaps a portion of the deceleration should be air-referenced), its simplicity renders it attractive. In any case, the command velocity profile should include both air-referenced and ground-referenced phases.

3. Deceleration profile

As has been discussed, most of the programs that included a prescribed deceleration used a constant deceleration profile for longitudinal velocity (References 1, 3, 10-14, 16-20, 28, 39, 42, 45, 48). One reason is the simplicity of the resulting guidance law ($\dot{X}_c \sim \sqrt{X}$), and another is the shorter period of time spent at low speeds when compared with an exponential deceleration ($\dot{X}_c \sim X$). The VALT program, however, noted that a constant deceleration for a helicopter requires increasing nose-up attitudes as hover is approached, to which the pilots objected, and instead used a constant attitude deceleration (References 15, 29, 30). The NASA SH-3A approach experiment also derived a ground-speed deceleration profile that essentially required a constant attitude deceleration (Reference 36). In the analysis of visual decelerating approaches given in Reference 50, an empirical fit to velocity-range data indicated increasing longitudinal deceleration with decreasing range; this type of profile would require even more increasingly nose-up attitudes toward hover, and might be hypothesized to be more objectionable than the constant deceleration.

It appears that the deceleration profile needs to be tailored, to some extent, to the control/display configuration of the helicopter. In particular, recall that the control augmentation used in the VALT experiments provided attitude command in pitch; hence, a profile which required constant attitudes to perform the deceleration resulted in minimal additional pilot workload (essentially

a trim change plus continuing attitude regulation). This type of profile appears to be "optimum" for situations in which rate damping, rate-command-attitude-hold, or attitude command control systems are used. For velocity augmentation/command control systems, however, the pilot does not directly command attitude in a helicopter, but rather longitudinal velocity. In this case, a constant level of deceleration is probably better matched to the aircraft's control characteristics; as pointed out in Reference 48, however, an acceleration command was preferred for the deceleration with this type of control system/approach profile combination, so that the pilot did not have to act as an integrator. An alternate, and perhaps preferable, profile for aircraft with velocity command control systems would be a series of step changes in commanded velocity. Further experimentation to devise such a profile on bases such as minimum fuel or maximum flight safety margins is recommended.

4. Lateral velocity profile

Essentially all of the programs have used what amounts to an exponential lateral velocity profile ($\dot{Y}_C \sim Y \Rightarrow KY - \dot{Y} = \varepsilon_{\dot{Y}}$) for localizer acquisition and tracking, generally converting it to a bank angle command. As is discussed in Reference 3, this type of profile could lead to large initial motions if the lateral offset is considerable and simultaneously the initial course is parallel to the approach centerline; although in practice such a possibility is remote because the pilot is generally given radar vectors to intercept the localizer at an angle like 30°, it is also useful to provide some command limiting (e.g. 30° in References 1, 3, 20, or 45° in Reference 48). Reference 3 also makes the point that this type of command implies a small commanded velocity for fairly sizeable offsets (e.g. a system designed for a 20 second time constant means that the commanded lateral velocity for a 100 foot offset will be 5 feet/second). Although this characteristic is beneficial in reducing the sensitivity of the command to position measurement errors, it does imply that

lateral position errors can remain fairly sizeable because of difficulty in making small changes in aircraft lateral velocity with respect to the earth ($\dot{Y} \sim u \sin \psi$). It is possible that a profile which commands a constant earth-referenced lateral velocity until quite close to the localizer, or one which commands a constant deceleration toward the centerline, might be preferable in this regard. In the absence of experimental or operational evidence demonstrating the suitability of other profiles, however, and the generally demonstrated suitability of the exponential profile, the lateral velocity commands should be of this type with a time constant of approximately 15 seconds.

5. Velocity command functional dependence

For the most part, the reviewed programs that required specific deceleration profiles derived the longitudinal velocity commands as a function of range-to-go (e.g. References 1, 10-20, 28-30, 36, 42, 45, 48). This method is the simplest in terms of the computations, but requires range information; range and/or range-rate data are also required to derive ground-referenced velocity status data unless an onboard INS is assumed. Strictly speaking, the characteristics of the approach position and velocity commands that were discussed above can be derived using altitude information instead (e.g. radar altitude or complementary filtered radar altitude and normal acceleration) in combination with glideslope and localizer data. The advent of MLS guidance systems obviates in general the necessity for the use of altitude instead of range information as the functional basis for the command computations, but some applications (e.g. night landings with visual landing aid glideslope lights) may require the altitude basis. In terms of pilot-centered control and display requirements, no fundamental difference between the methods exists.

4.2 Control-Display Combinations

As should be clear from the previous discussions, control system characteristics should be discussed in the context of the appropriate display system. In this subsection, candidate control systems that may be suitable for performing the approach profiles described above

under instrument conditions are hypothesized, as inferred from the work reviewed previously, with a general definition of the displayed information required. The following subsection discusses more fully specific display considerations, and the final subsection summarizes the control-display combinations suggested for further comparative examination.

4.2.1 Rate Damping in Pitch/Roll

In spite of the fact that none of the reviewed programs which considered control systems including only rate damping in pitch and roll showed consistently satisfactory performance during decelerating instrument approaches to hover, it is difficult to exclude totally from future consideration this type of system, if only because it is simple and compatible with limited-authority series servo implementations. It is clear, however, that the following points are important with such an implementation:

- The pilot workload in pitch and roll will be highest with this type of system. As a result, the primary display must be an integrated electronic instrument giving position and velocity status data plus three-axis control directors (References 1, 10, 15-20, 26).

- The suitability of such control systems will be quite configuration dependent. It appears that the unaugmented airframe characteristics must be such that rate damping in pitch and roll will result in:

  1. No unstable -- or at least barely unstable -- roots at hover (References 1, 15, 20, 27). The inherent characteristics of tandem rotor helicopters, for example, probably preclude this type of pitch augmentation (Reference 15).

2. Primary pitch and roll responses that exhibit time constants between 0.25 and 0.4 seconds (Reference 54).

3. "Small" longitudinal-lateral coupling may be hypothesized as a requirement, although specific values of "small" are not defined.

- The pilot will be required to devote considerable attention to pitch and roll. Accordingly, directional and vertical control characteristics must be good (References 3, 4, 16, 20), and augmentation in these axes is probably required.

- This type of control system does not regulate well against pitch and roll disturbances caused by turbulence; hence, aircraft with "higher" moment sensitivity to gust inputs (e.g. some "rigid" rotor designs) may not be amenable to rate-damping only.

The need for an integrated electronic display may be inferred from the JANAIR (References 10-14) and PIFAX-H (References 4-9) studies, which resulted in an electromechanical instrument specification and did not demonstrate good system suitability in flight; the requirement for 3-axis control directors was pointed out earlier in the summary of the literature review. General display considerations for this display are given in the next subsection. It may be assumed that effective augmented values of $M_{\dot{q}}$ and L_p in and near hover should be around -3.0 1/second from the Reference 54 experiment; the X-22A (Reference 1) and CL-84 (References 3, 16) augmentation were of this order, and such a level appears to be consistent with limited authority series servos (e.g. the AH-1G SCAS design, References 27, 55).

As was also pointed out earlier, directional augmentation more complex that rate damping appears to be a requirement. Yaw

rate-command-heading-hold is desirable for hover (References 1, 4, 20, 26); an initial estimate of a 1.0 second time constant is consistent with the values used in References 1, 20. Turn-following (sideslip suppression) has been noted as important in most of the experimental studies (References 1, 8, 15, 16, 20); the level of augmentation used in Reference 1 was based on the requirements of MIL-F-83300 (Reference 56) and was suitable, but additional parametric studies are probably required to define "good" turn-following performance in the context of the deceleration instrument task. For single-rotor helicopters, it has also been noted that suppression of directional perturbations caused by collective blade (power) inputs is desirable (Reference 4). It should also be noted that sideslip suppression at low speeds may define a requirement for a low-speed air sensor, although use of side acceleration, roll-rate-to-rudder, and lateral-stick-to-rudder have been used in lieu of such a sensor; as will be discussed, airspeed sensing accurate to zero airspeed is essentially a display requirement for instrument hover also.

None of the programs reviewed considered rate damping in combination with some augmentation of the vertical axis. A valid argument against such a control system is the increased complexity and particularly the flight safety considerations. On the other hand, several helicopters exhibit vertical velocity responses at low speed with time constants between 2.0 and 3.0 seconds, which implies imprecise vertical tracking performance without pilot compensation. Augmenting the vertical damping to achieve time constants of 1.0 seconds or better would improve this situation (Reference 1); reduced pilot attention to the vertical axis would result from the improved damping and permit more attention to attitude control.

It is emphasized again that the work which was reviewed indicates that, at best, a control system employing only attitude rate damping in pitch and roll will be marginally satisfactory for the instrument decelerating approach task. By virtue of

the preponderance of such systems in currently operational helicopters, however, it still seems useful to conduct a parametric investigation of typical response characteristics assuming a control system implementation as described above and an "optimized" display. Such an investigation is recommended for future research.

4.2.2 Rate-Command-Attitude-Hold in Pitch/Roll

With this type of control system, the pitch and roll responses to pilot inputs exhibit rate command characteristics as in the rate damping control system, but feedbacks of pitch and roll attitude are used to regulate against external disturbances when no pitch/roll inputs are commanded, which is a major advantage of the rate-command-attitude-hold implementation. Basically, two types of implementation may be considered: continuous feedback of attitudes with an integrator in the forward loop (References 1, 48), or switched in attitude feedbacks when the pilot's input (usually sensed by force) is less than a threshold value (References 20, 26, 40). The latter implementation is particularly suited to control systems with limited authority series servos, and in fact requires essentially no more authority than the rate damping type.

Given the similarity in commanded response type to the rate damping system, the same requirements for an integrated electronic display with three-axis control directors plus directional augmentation as discussed above may be inferred (References 1, 3, 48). It is likely that vertical augmentation would be desirable here also, as discussed for the rate-damping system, although possibly the attitude stabilization against external disturbances feature of the attitude-hold would obviate this requirement; the reviewed programs did not consider such a combination and do not therefore provide explicit guidance. Again, the rate response time constants should be on the order of 0.25 to 0.4 seconds. The level of attitude feedback may be picked on bases such as actuator authority

or the amount of stabilization of unstable roots required; in Reference 20, values which gave natural frequencies ranging from 1.0 to 2.0 rad/sec were considered.

This type of control system still requires the pilot to perform visual closure of attitude, velocity, and position control loops; its primary advantage is the regulation against external disturbances or inputs from other controllers plus its capability with limited authority implementations. Of the reviewed programs, very few considered it for hover: in general, attitude command characteristics at hover are blended to rate-command-attitude-hold characteristics in forward flight (References 43, 48). Some of the X-22A results (Reference 20), however, indicate that the enhanced stabilization compared to rate-damping-only does in fact result in increased suitability for the instrument decelerating approach.

4.2.3 Attitude Command in Pitch/Roll

A control system which provides attitude command augmentation in pitch and roll at low speed and hover has been demonstrated to provide a satisfactory decelerating instrument approach capability with a variety of displays in most of the programs that were reviewed (References 1, 20, 29, 33, 36, 39, 40, 42). Although the suitability of the rate-damping and rate-command-attitude-hold implementations discussed earlier for the complete decelerating task is perhaps conjectural, there is really little question regarding the usefulness of attitude command augmentation. As was discussed earlier, this type of control system not only stabilizes the characteristic roots of the aircraft but also provides a force cue to the pilot concerning aircraft attitude; hence, requirements for visual closure of the attitude control loops are reduced, permitting increased attention to the velocity loops and perhaps reducing some of the information requirements. The questions that have not been completely answered by the literature are:

- The level of augmentation required and the impact of limited authority series servo implementations.

- Augmentation requirements in the directional and vertical axes.

- Display information and presentation variables.

A fairly wide range of augmentation levels was considered in the reviewed programs: pitch natural frequencies of 4.0 rad/sec in HOVVAC with a 5.0 rad/sec first order prefilter (Reference 43), of 4.0 rad/sec in the first X-22A experiment with a 2.0 rad/sec second order prefilter (Reference 1), of approximately 1.6 rad/sec in the CH-53 programs (References 31-33, 35, 36, 39), of 1.4 rad/sec in the VALT experiments (References 15, 29, 30), and of down to 1.0 rad/sec in the second X-22A experiments (Reference 20). The visual hover simulation study of Reference 54 showed ratings of satisfactory for natural frequencies ranging from approximately 1.0 to 3.0 rad/sec, with a slightly higher upper limit experienced in flight with the X-14. Since the attitude feedback gain is essentially proportional to the square of the natural frequency, implementations which are built around limited authority series servos clearly should use the lowest possible natural frequency; in the second X-22A experiment, for example, ratings of marginally satisfactory (PR = 3 to 4) were obtained for a natural frequency of 1.0 rate/sec implemented through a 20% series servo. On the other hand, the lower the augmentation, the less the regulation against external disturbances or other control inputs; in addition, the pilot may have to overdrive the attitude loop to achieve satisfactory velocity control bandwidths. It appears that a reasonable compromise is a natural frequency of approximately 1.5 rad/sec, with control sensitivities on the order of 10°/inch.

The reviewed programs indicate that directional augmentation of the type recommended for the two previous control systems

be used for the attitude command system also. References 1, 15, 28-30, and 43 (X-22A, VALT, HOVVAC) used turn-following augmentation for the approach, and References 1, 15, 28-33, 35, 36, 39-41, (X-22A, VALT, ITED, CH-53) included heading hold augmentation for the hover. It would appear from all of the programs that vertical augmentation is not required when attitude command in pitch and roll is used, but some caution should be taken in this interpretation. The initial ground simulation for the VALT program found that vertical augmentation was required to perform the decelerating task (Reference 28); although flight tests demonstrated satisfactory task performance without vertical augmentation when three-axis control directors were used (References 29, 15), the addition of vertical augmentation improved performance and reduced pilot workload considerably (Reference 30). In the first X-22A experiment (Reference 1), a specific control-display trade-off in the vertical axis was seen, and a thrust magnitude director was required when thrust inclination was changed manually and the vertical axis was not augmented. The simulation of the AV-8B in the second X-22A experiment (Reference 20), however, showed no need for a vertical director, possibly because of the less precise deceleration profile considered. It would be useful, therefore, to examine systems both with and without vertical augmentation given a display which does not include a thrust magnitude control director.

It is evident from the reviewed programs that, with attitude command in pitch and roll, some latitude in the displayed information level and method of presentation exists. If velocity and position status and command information are given in a fairly integrated fashion, it has been shown that pitch and roll control directors are not required for the decelerating instrument approach and hover (References 1, 20, 31-34, 36). It may also be true, based on References 15, 29, 30 (VALT) and 42 (ECOM operational) results, that integrated electronic display presentations are not a strict requirement if 3-axis control directors and suitable

velocity and position data are shown electromechanically; the results of References 1 and 35, however, tend to show that electromechanical instruments are likely not well suited to the tasks even with attitude command unless carefully arranged and augmented by additional velocity instruments. As was discussed above, some question remains regarding the necessity for a vertical control director, depending upon the amount of vertical damping. On these bases, assuming attitude command augmentation ($\omega_n \cong 1.5$ rad/sec) in pitch and roll and a dual-mode directional augmentation system, the following configurations are warranted:

- Vertical augmentation, integrated electronic format (IEF) without control directors.

- No vertical augmentation, IEF without control directors.

- No vertical augmentation, IEF with thrust magnitude control directors.

- No vertical augmentation, electromechanical displays with 3-axis control directors.

Additional considerations regarding the details of the displays are discussed in a later subsection.

A final point regarding the implementation of an attitude command system should be noted. It is clear that these characteristics, while appropriate for tracking, deceleration, and hover, are not correct for up-and-away flight or localizer acquisition, primarily in roll. For this reason, the implementation should consist of rate-command-attitude-hold (or even rate-damping) with a changeover to attitude command at some point in the approach. The majority of the programs made the change as a function of velocity (e.g. References 43, 48), but this logic is not overpoweringly attractive, as the response characteristics the pilot sees will change in the middle of the deceleration. A procedure that would appear preferable is to make the change when the initial deceleration is commanded, and this implementation should be considered.

4.2.4 Horizontal Velocity Augmentation/Command

There exists an intuitive appeal to providing the pilot with direct control of the aircraft horizontal translational velocities, particularly of longitudinal velocity and particularly in the hover. If this desideratum can be achieved, the pilot in principle does not need to close the inner attitude loops himself, and therefore is provided with essentially integral control of position, at least in hover. In Reference 57, an analytic study was conducted for the CH-47 helicopter assuming an optimal control pilot model, from which it was predicted that satisfactory system performance for instrument approaches could only be achieved with a velocity command control system. Reference 58, another analytic control system design study, also concentrated primarily on a velocity command control system for similar reasons.

Practical implementations of velocity command systems in the literature are relatively sparse, however. The only helicopter application extensively flight tested was the TAGS program (References 46, 47); flight tests of a longitudinal-vertical system were also conducted with the X-22A, while some ground simulation examinations were performed in the VALT (Reference 28), NASA (Reference 48), and ITED (Reference 33) studies. Two primary difficulties must be solved for the helicopter application and account in part for the limited testing of such systems:

- The control law structure is complex, and in particular the need for accurate groundspeed or airspeed information at low speeds is a difficult sensor requirement.

- For helicopters, no independent control effectors exist to command longitudinal or lateral translational velocities independently of pitch/roll attitudes; hence, direct control of attitude is not available to the pilot, and the attitude responses to control inputs depend on the

design criteria of the velocity command system plus inherent characteristics such as drag damping (X_u).

Because of the limited experimental/operational experience, it is difficult to propose well-validated control system design guidelines. The generic ground simulation of References 54, 59 indicated a "best" cubic frequency of approximately 2.0 rad/sec for a particular form of feedback laws; the attitude numerator zero value is not clear, however, nor is the form of attitude response, therefore. The analytic design of Reference 58 was made using a set of a priori time history criteria, but their selection appears to have been arbitrary. It is clear that additional experimental work in this area is required, preferably with a flight vehicle, to investigate a parametric range of response characteristics for this type of control system. In the absence of such information, an effective augmented value of M_u (or L_v) between .025 and .05 would yield the "frequency" found good in Reference 59, with attitude rate and attitude feedbacks selected to be sufficient to give near critical damping at a frequency between 1.0 and 2.0 rad/sec. Values for vertical velocity response to collective stick inputs should probably be time constants between 0.5 seconds (Reference 1) and 1.5 seconds (Reference 46).

The use of velocity command augmentation longitudinally and laterally implies special attention to controller characteristics and to what each controller commands. For example, the TAGS sidearm controller did not use a centering spring initially for longitudinal velocity commands; the force the pilot felt was proportional to how fast he made the input and hence, to a degree, provided a command acceleration cue (Reference 46). This implementation was found to give poor hover tracking, and a centering detent was added for later flight tests (Reference 47). In Reference 48, it was found that commanding longitudinal velocity through the decelerating part of the approach was less suitable than commanding longitudinal deceleration; in hover, however, a switch to velocity command had to

be made. The controller in this case was a thumbwheel with no centering spring, and ride qualities (horizontal accelerations) problems were also encountered. As with the aircraft response characteristics, it is not entirely clear what the controller characteristics should be, and further investigation is warranted.

It is also important to ascertain whether the added complexity of velocity augmented control systems -- particularly laterally -- really provide enhanced task performance. In the Reference 1 X-22A experiment, for example, performance analyses showed that the major benefit of the velocity command system that was investigated was in the vertical axis, and little longitudinal deceleration tracking improvement was apparent. It is clear that, for touchdown, the pilot must have direct control of aircraft attitude: in the TAGS design, the original implementation reverted to attitude command when two wheels were on the ground, and it was found necessary to modify the logic to a switch when only one wheel had touched (References 46, 47). For this reason, it would be useful to consider a control system in which longitudinal and vertical velocity command augmentations were used in conjunction with roll attitude command, in addition to the full 3-axis velocity command concept of TAGS.

It is also not clear that velocity command augmentation is proper if the landing pad is moving. For example, in Reference 60 a series of measurements of shipboard landings is reported, and it is noted that the pilots were not generally consistent in making the instant of touchdown coincide with a level deck. Because the helicopter does not in general have independent force effectors for translational rate command, it is therefore important that velocity command attitude command implementations be directly compared for the task of landing on a moving platform.

Although some aspects of a velocity command system are difficult to define, one point that is clear is the reduced sensitivity of system suitability to display information nuances. Both

the X-22A (Reference 1) and TAGS (Reference 47) programs demonstrated satisfactory performance of decelerating instrument approaches with no control director information. It is, in fact, possible that separated electromechanical displays can be suitable as well as integrated electronic format. Both types of displays, incorporating velocity status and command information but without control directors, should be examined.

4.3 Display Considerations

As is evident from the summary of the literature review given earlier, it is difficult to group conveniently the display characteristics in the same fashion as was done for the control systems. To provide a framework for a discussion of display considerations, therefore, the by now "classic" AGARD review of V/STOL information concepts (Reference 61) and the survey results given in the first JANAIR report (Reference 10) can be combined into a list of information requirements for instrument decelerating approach. Table 4, taken essentially from Reference 1, gives such a list. On this basis, lessons learned from previous programs can be related to specific information requirements.

1. Pitch and Roll Attitude

The pitch and roll information is of prime importance essentially irrespective of control augmentation. Strangely enough, this point seems occassionally to have been lost, particularly in the design of electronic formats (e.g. Reference 31). The information should be centrally located and present precise data; again, these points seem obvious, but the variety of displays examined in the referenced programs achieve them with only varying degrees of success.

With regard to pitch attitude information precision, a 3-inch ADI approximately one-half meter from the pilot's eye attenuates pitch angle information about 16:1 compared to the real world. This size of ADI was considered to be inadequate for helicopter IFR early in the PIFAX-H program (Reference 4), and one display improvement considered was a 6-inch ADI to improve the pitch attitude sensitivity (approximately 8:1); the KLM instrument complement also includes a 6-inch ADI (Reference 37).

TABLE 4.- INFORMATION REQUIREMENTS FOR INSTRUMENT DECELERATING APPROACH

Information level	Requirement
Orientation	Pitch, roll, and heading; desired approach course
Position status	Height - radar altitude (baro. alt. for initial approach) Range-to-go Relative bearing of touchdown point
Velocity status	Airspeed and groundspeed Ref. 61: Airspeed for aerodynamic lift regime, groundspeed for powered lift regime, smooth transition between A/S and G/S Ref. 10: Both required Instantaneous vertical velocity
Position error	Vertical and lateral flight path error (approach) Longitudinal and lateral position error (hover - Ref. 10)
Velocity error (ref. 61)	A/S-G/S deviations Vertical speed deviation
Miscellaneous (ref. 61)	Thrust vector angle Torque (or thrust) Angle of attack and limits - Aerodynamic lift only Sideslip or lateral acceleration and limits Wind vector Maximum available thrust or torque; time

With electronic displays, the selection of pitch attitude scaling is essentially at the designer's discretion. Values have ranged from approximately 16:1 head-down (e.g. the first X-22A experiment, Reference 1) all the way to 1:1 head-up (e.g. the Phase II CL-84 experiment, Reference 17). In Reference 20, the 16:1 scaling was compared to a 3:1 scaling for equivalent information levels, and the same control systems, using a HUD format; the airplane was considered "sluggish" with the 16:1 scaling (for an attitude command control system) and "too sensitive" with the 3:1 scaling. Even the 8:1 scaling examined in the PIFAX-H program was considered too sensitive (Reference 7), although 5:1 scalings were used in the Phase I CL-84 HUD formats with no complaints (Reference 16); the 1:1 scaling in Phase II of the CL-84 may have caused the comments concerning attitude control difficulties (Reference 19).

As can be seen, the determination of the "best" pitch attitude sensitivity has not been made, and, in fact, considerable controversy regarding this subject still exists. The proponents of 1:1 scaling for head-up displays are on shaky ground: there is no a priori necessity for direct overlay on the visual scene, and the limited vertical field-of-view (FOV) of most HUD devices implies a full scale attitude deflection for only 10 degrees, approximately, thereby exaggerating pitch rate motions. In practice, the two important considerations are:

- available FOV (e.g. panel room for larger ADI or CRT, optics of HUD)

- aircraft control sensitivity (angular rate or attitude developed per unit control deflection) as well as aircraft longitudinal stability characteristics.

The latter consideration is flying qualities related: to the pilot, the response characteristics in pitch attitude under instrument conditions are observed essentially from the attitude display, and he cannot distinguish (to some extent) between aircraft control sensitivity and display sensitivity. It would appear that,

in general, an attitude scaling somewhere between 10:1 and 5:1 attenuation is appropriate either head-up or head-down; a 5-inch ADI, for example, fits into this range.

It is also important that the pilot be able to discern easily the magnitudes of pitch and roll attitude. A disadvantage of many electronic formats using a single line for the horizon (e.g. References 1, 21, 24, 31-34, 39) is that quantitative pitch information is not available. Unless a separate roll pointer and index is used as in Reference 20, the same difficulty applies to roll. "Ladder" type presentations typically used in HUD presentations (e.g. References 16-20, 48), while presenting more attitude lines, generally have the "rungs" broken in the middle, which was considered undesirable in the Reference 20 experiment; again, no separate precise roll information is generally provided. Electromechanical ADI instruments can be better in this regard: quantitative pitch increments are generally provided on the ball, and a roll pointer at top (or bottom) is also typical. Although some display clutter accrues for electronic instruments by including additional attitude references, this addition to the simple horizon line formats appears warranted. Further, the fixed aircraft symbol should be designed as a good zero reference for both pitch and roll (the circle of Reference 1, for example, was inadequate).

2. <u>Heading, Turn-rate, Slip</u>

It was pointed out in pilot surveys (References 4, 10) that helicopter instrumentation is typically deficient in the presentation of heading, turn-rate, and sideslip information. Part of the difficulty is the use of separate instruments in many applications. If electromechanical instruments are used, an ADI with integrated turn-slip needle and ball can resolve part of the information separation problem, although a separate HSI is still the source for heading information (References 7, 9, 14, 22, 29, 42). With electronic displays, the possibility of integrating all of this information on the primary display

exists, but the manner in which it is presented is important. The Phase II CL-84 format used an analog cursor on the zero-attitude horizon bar (scaled 1:1 with the outside world) plus a separate digital readout of heading; this format was considered poor because the cursor could be off-scale easily (lateral FOV) and no rate information was available from the digital readout. The first X-22A experiment (Reference 1), and early ITED formats (e.g. Reference 31), used an analog heading "tail" on the aircraft symbol, but this version was not considered too good either.

A better method is that used in the Phase I CL-84 format (References 16, 17) and the second X-22A experiment (Reference 20), both of which consisted of a moving heading tape above a lateral acceleration ball at the bottom of the display. It has been noted in human-factors-oriented display research that "rate-field" presentations are advantageous for some types of information (References 62, 63); a moving heading tape is of this type, and presents implicit turn rate information plus precise heading angle data in an easily assimilated fashion. Combining the lateral acceleration ball and heading tape at the bottom of the display gives the inner loop directional data in an integrated fashion and in the general location the pilot is used to from ADI/HSI presentations.

3. <u>Vertical Position/Velocity Status, Command, and/or Error</u>

Almost all of the reviewed programs noted that altitude control during descending decelerating approaches is a crucial workload item for helicopter or V/STOL instrument operations (e.g. References 1, 13, 16, 19, 28); as has been discussed, vertical augmentation appears necessary for the less "complex" angular augmentation control systems because of the altitude control problem. The control difficulties are exaggerated by the fact that, as is pointed out in the AGARD summary, height and height rate information appears to be the most difficult to present in integrated

electronic formats (Reference 61). This latter point is borne out by the lack of uniformity of the methods used to present these data in the programs that were reviewed. Accordingly, guidelines must be inferred indirectly from previous experience.

Consider initially the location of the altitude and rate-of-climb information relative to the attitude presentation. For helicopters and most VTOL aircraft, the majority of the decelerating approach is performed on the "backside" of the power curve. The appropriate control for rate-of-descent is therefore thrust, the controller for which is always a left-hand operation (collective stick). In spite of the human factors desideratum of having the information located according to the control used, a surprisingly large number of the reviewed programs retain conventional (CTOL) aircraft practice and place altitude and rate-of-climb information in either a central location or on the right side of the attitude presentation (e.g. References 15-19, 24, 29, 30, 38, 39, 48). Such locations can tend to induce the pilot to use the longitudinal stick as an altitude controller, and have been shown to be non-optimum (References 16, 20, 48). A general principle which should be adhered to, therefore, is to place this information on the left of the attitude presentation. This principle is followed by KLM for instrument operations using electromechanical instruments in the close-scan "reverse T" panel layout that is used; it was also followed in the X-22A programs (References 1, 3, 20), JANAIR studies (References 10-14), the ITED studies (References 31-34), and during the TAGS instrument approach examination (Reference 47).

Given the precept that altitude and altitude-rate information should be shown on the left, the next questions are whether pursuit (i.e., status and command) or error (the difference between status and command) information should be given, what form (analog or digital) the information is presented in, and the scalings used to present the information. Not all of these questions can be definitively answered, but some inferences can

be drawn. With conventional dial counter-pointer electromechanical altimeter and IVSI instruments, the status information is given but it is difficult to incorporate integrated command or error information. Because of the physical separation of the instruments, a separate altitude error (e.g. glideslope error) can be incorporated on the left side of some electromechanical ADI units (e.g. Reference 9, although it was shown on the right hand side), but it is difficult to show also rate-of-descent error. If electromechanical instruments are to be used, a preferable type appears to be tape-with-moving-pointer instruments, as used in the TAGS (References 46, 47) and the NASA SH-3 (Reference 36) programs, partly because they can be located in closer proximity to each other and the ADI than can dial-type instruments, and partly because, as was demonstrated in Reference 36, clever arranging of the scales can be used to incorporate some command information.

With electronic displays, the choices are broader, and the answers to the questions given above become more important. Consider initially the question of pursuit versus compensatory presentations. It is generally considered correct that pursuit displays -- showing both status and command value data -- permit the pilot to generate additional lead when compared to compensatory displays, and thereby improve tracking performance (References 62-64); in fact, References 62 and 63 go so far as to suggest that attitude information be presented in a combined pursuit/compensatory fashion because of this feature. An additional obvious advantage of pursuit presentations is that they explicitly include precise status data; compensatory presentations, which display only the error between the command and status information (e.g. glideslope error), may require separate status presentations.

On the other hand, compensatory presentations, because of the integration of status and command data into one error datum, can alleviate display clutter: for altitude and altitude-rate displays, the reduction is from at least four to only two symbols. An example of perhaps excessive clutter for the VTOL application

is the pursuit format used in Reference 48, which in fact only used pursuit philosophies for altitude rate, and used a compensatory error plus digital readout for altitude. Compensatory presentations also permit information scaling to be more sensitive than pursuit formats which used a fixed scale, because only the error determines full scale.

The advantages of the compensatory presentation of fewer symbols and more sensitive scaling are particularly important for altitude and altitude-rate data because of their relationship to each other. Simplified greatly, altitude control dynamics near the hover have second order dynamics when the pilot closes an altitude-rate and altitude loop. The scalings of altitude error and altitude-rate error information, as well as the senses of the symbol movements, can be selected to provide a quasi control director for the thrust controller (Reference 1). In this way, the status error information can provide assistance in how to control altitude.

It appears desirable, therefore, to provide the altitude-rate and altitude error information explicitly, but it is also clear that absolute status data for both altitude and rate-of-descent should be given (Reference 20). One way to resolve conflicting requirements of scaling is to use moving tape formats for altitude and altitude-rate, so that command and status indices can be scaled to the desired sensitivity. This approach would seem to meet both absolute and error status requirements, in fact is of the type of frequency splitted pursuit-compensatory information presentation espoused in References 62, 63, and uses some rate-field display concepts. An example is constructed schematically in Figure 2.

This suggested means of presenting the altitude and rate-of-descent information also meets (or appears to meet) additional requirements. One of these requirements is that altitude error be given in lineal rather than angular fashion (Reference 17, for example): that is, full scale error deflection should correspond to a

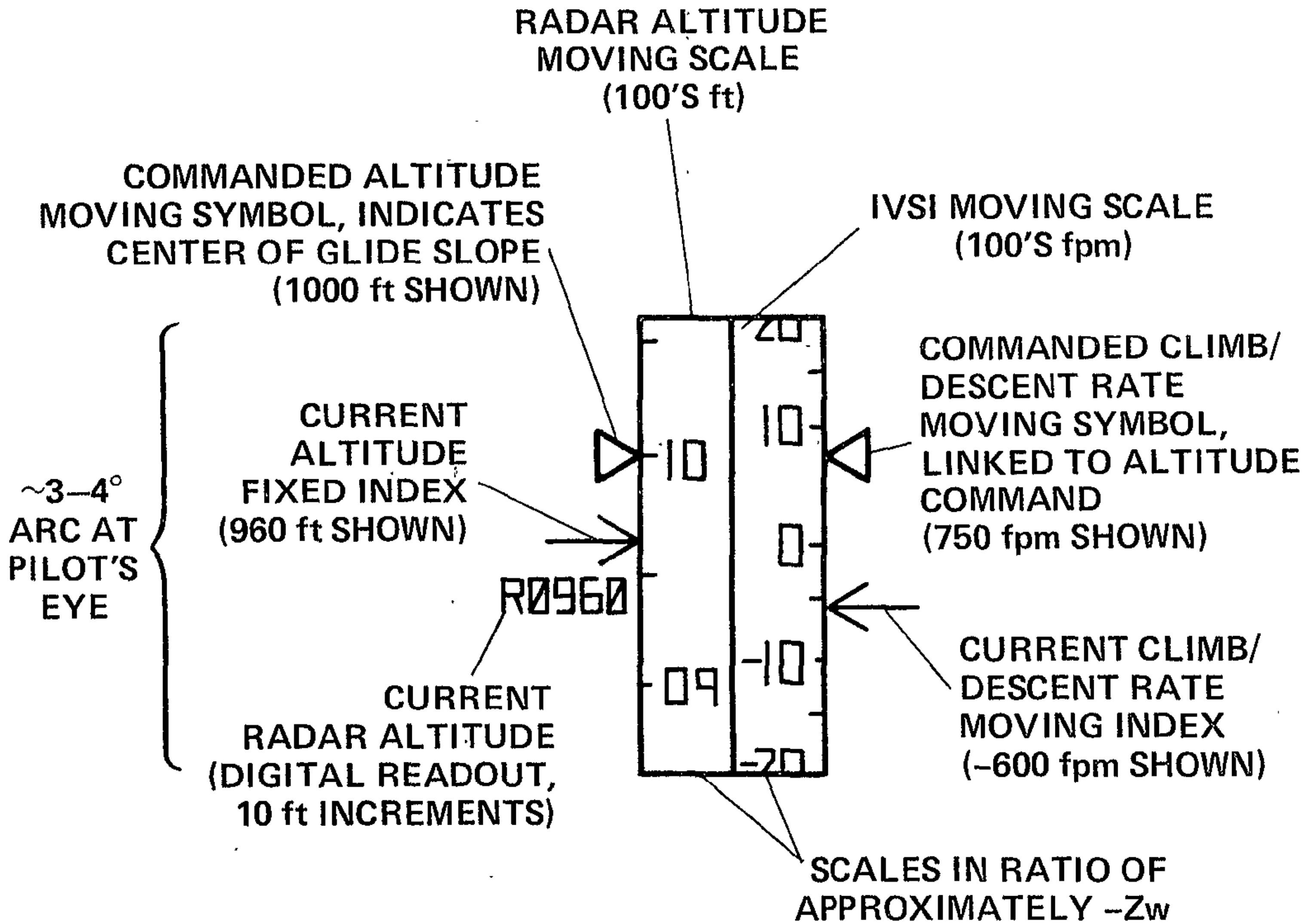


Figure 2.- Possible vertical situation/command information display.

specific constant altitude irrespective of range. Raw glideslope deviation information violates this requirement. Another apparent need is to have altitude information given in analog format at low altitude (Reference 61). This need was achieved in several programs through the addition of a "rising runway" symbol activated during the final 500 feet (for example) of altitude (References 9, 42, 48); it was noted in Reference 19 that digital altitude information alone was not appropriate at low altitude because of the lack of trend data. A moving tape format should supply adequate analog information to obviate the need for a rising runway symbol.

The selection of the display sensitivities for altitude and altitude-rate error symbols is extremely important to pilot control. It is possible only to estimate appropriate values on the basis of previous work, however, and additional research may be required in this regard. It has been noted that the altitude and altitude-rate error signals can (and should) be used in conjunction to provide a quasi control director. On this basis, manual control theory may be used to define an appropriate relationship between the two scalings. Reference 1 shows that, for a thrust magnitude control director, an appropriate ratio between the gain on altitude error and that on altitude-rate error is one that is approximately equal to the vertical velocity damping -- i.e. $K_z/K_{\dot{z}} \cong - Z_w$. It is straightforward to show that, for the senses of the symbols hypothesized in Figure 2, this value is also correct for the individual error scaling sensitivities ratio; hence, the ratio between full scale altitude error and full scale altitude-rate error should be on the order of $-Z_w$. For example, a typical hover value for helicopters is $Z_w = -.33$. If full scale altitude error is selected to be $\pm$ 100 feet, then the full scale altitude-rate error should be approximately + 33fps, or approximately $\pm$ 2000 fpm, which is the scaling shown on Figure 2.

It is not particularly clear, however, what the best scaling sensitivity for altitude error is. In Reference 1, the full scale

error was ± 100 feet, corresponding to approximately ± 2 1/2° at the pilot's eye; in Reference 20, ± 75 feet corresponded to ± 2 1/2° for one format and ± 4 1/2° for another, and the latter scaling appeared perhaps too sensitive. Most of the programs which displayed angular rather than lineal deviations on HUD formats appear to have used 1:1 scaling (e.g. Reference 17): a 100 foot deviation showing as 2 1/2° corresponds to a range of approximately 3000 feet, with the scaling being more sensitive closer in, which is why angular deviation presentations do not appear to be appropriate. At the present time, it appears that a reasonable scaling is on the order of 3°/100 feet, but additional studies are probably warranted.

4. Horizontal Position

While the requirements for cross-track and range-to-go position information are fundamental to the decelerating approach control problem, the reviewed programs have used a variety of means to present these data, and no clear distinction as to the best form is apparent. In particular, the following questions are of interest:

- For electromechanical instruments, how much integration of range and cross-track information can be made?
- Should cross-track data be error or absolute?
- Should range data be digital or analog?
- With electronic instruments, should the information be based on a vertical or horizontal view?
- If a horizontal view is used, should the reference coordinates be approach-course-up or aircraft-heading-up?
- With HUD instruments, should overlay (e.g. runway) techniques be used?

The programs that have used electromechanical instruments tend to favor some sort of moving map separate horizontal information display (References 15, 29, 30, 47), which presents absolute cross-track and range information in an analog fashion. As is noted in References 1 and 29, the separation of this information can be a problem with rate or attitude augmentation control systems, and care must be taken to reproduce some of the primary information on the horizontal display too. When control directors are used with an electromechanical ADI, it is generally not possible to show raw localizer error. This lack of capability is a problem, since the lateral position is essentially a continuous control for the entire approach, whereas longitudinal position (range) is really controlled directly only at and near hover; if the error can't be shown on the ADI, the separate horizontal position display must be used to check the lateral position status. It is possible that an additional tape meter, placed horizontally between the ADI and moving-map or HSI and showing localizer error, as was done in Reference 36, would be beneficial in this regard.

The majority of the programs have presented absolute rather than error cross-track (lateral) position information (References 1, 10-13, 15-21, 29-34, 36, 39, 47). With electronic formats, this choice is easy to implement, and provides some of the advantages of pursuit-type displays. As has been noted, with electromechanical instruments a separate display is required to present these data this way, but it is likely necessary to do so at least for the hover portion of the task. In Reference 20, it was found that, if the majority of the deceleration was performed on instruments but the hover was visual, lateral error information was sufficient, corresponding to the CTOL approach situation; hence, the requirement for absolute position information is primarily hover and low-speed oriented, and it may not be necessary to show the information this way for the entire approach.

Similar considerations apply to the presentation of range information, with the difference being a question of digital versus

analog presentation instead of absolute versus error data (range error is a meaningless concept unless "4-D" -- including time -- guidance is used, which is not considered here). If range information is presented in analog form (i.e. movement of a symbol representing the landing pad), discrete or nonlinear scaling changes must be made, at least if the information is given in horizontal (or plan view) format (References 1, 10, 15, 16, 20, 29, 30); this problem is not as prevalent with vertical view presentations (e.g. runway overlay), however, because of the geometry of the situation. It may not be necessary, however, to present range information in analog fashion except near the hover, because it is not continuously controlled until that point. Given the type of approach geometry recommended earlier, it would appear that a sensible choice would be to give digital range information until the level-off point, and analog information in addition to digital from there to the hover point; a procedure somewhat similar was employed in Reference 48. An additional advantage to this procedure is that changing the symbology at this point provides a "command" cue to the pilot regarding the change from descending to level approach.

With integrated electronic formats, the presentation of analog cross-track and range information can emphasize either a vertical view or a plan view format. HUD formats frequently have taken the vertical view approach (e.g. References 17-19, 21), although mixed vertical-horizontal formats have been shown to present no problems to a pilot in a HUD presentation (References 16, 20). The JANAIR studies examined electronic formats based on both types of presentation, and found essentially no difference (Reference 10). Since, in the hover particularly, it is longitudinal and lateral position that must be controlled precisely and simultaneously, a plan-view presentation seems intuitively somewhat preferable (References 1, 31-34).

Given the assumption of a plan-view presentation, some debate has concerned whether the coordinate system used should be referred to the ground approach course ("approach-course-up") or the aircraft body axes ("heading-up"). The JANAIR studies recommended

a heading-up presentation for hover (Reference 13); with this coordinate system, the pilot can essentially push the stick in the direction of the landing pad without having to make a mental coordinate transformation, a mental process which some research deems to be bad (Reference 62). The ITED studies, on the other hand, emphasized approach-course-up presentations (Reference 31); this coordinate system is particularly suited to localizer acquisition tasks as well as cross-range tracking during deceleration in cross-winds (Reference 1). In the X-22A experiments, a compromise was achieved by linking the presentation coordinates to the type of (dual mode) directional augmentation selected, with the heading-up format corresponding to the heading-hold directional augmentation used for hover (References 1, 20). Given the switch from digital to analog range information discussed earlier, a reasonable procedure might be to use a line representing the approach course, shown in approach-course-up coordinates, and then, when the pad is initially shown at the level-off point, to present it in heading-up coordinates as was done in Reference 48. It seems preferable, however, to have the format coordinates change under pilot control, and so the procedure used in the X-22A experiments appears best.

With a plan-view format, the question of one-to-one overlays with the real-world in HUD presentations does not really arise, but the subject appears to warrant discussion anyway. The AGARD report (Reference 61) makes the point strongly that showing a perspective runway on the HUD for overlay on the actual runway may not provide the required assistance at all. Further, attempts to use overlays in VTOL aircraft have been hampered by large crab angles that can be attained by the aircraft in crosswinds (Reference 18). It appears, on these bases, that one-to-one overlays should be eschewed for helicopter applications, and that more symbolic forms of giving the position information -- such as those suggestions given above -- are preferable.

5. Horizontal Velocities

It is a requirement for instrument hover that horizontal translational velocities be shown explicitly (References 1, 3, 13, 20, 31, 32, 36, 47). From the Reference 1 results, this requirement appears to exist regardless of the type of control system that is implemented. Further, since during the deceleration a non-constant longitudinal velocity command must be tracked, it is likely that an analog presentation of the velocity status and command information is required for precise deceleration. As was discussed earlier with regard to guidance computations, the question of whether airspeed, groundspeed, or both should be displayed may also be raised. Of importance also is the scaling of the longitudinal and lateral velocity data presentation, in the same way as for the vertical velocity presentation.

With electromechanical displays, the tape-type instruments used in the TAGS (Reference 47) and NASA SH-3 (Reference 36) programs appear to be the best solution. A longitudinal ground speed tape should be placed to the right of the ADI, as was done in the TAGS program (Reference 47), but should probably also be repeated beside the moving map. A clever way to give commanded longitudinal velocity is the procedure used in Reference 36, which consists of a longitudinal range tape placed next to the velocity tape and scaled such that the range status indicator provided a commanded velocity. Lateral velocity should be a horizontally placed tape below the ADI, again as in Reference 47. It is reasonable that these velocities be with respect to the ground (References 36, 47), and referred to the approach course coordinate system.

With electronic instruments, a wide latitude of possibilities again exists. Although Reference 61 recommends the display of longitudinal speed error, and such a symbol was found necessary in the Phase II CL-84 experiment (Reference 18), in Reference 1 this error datum was found to be redundant if absolute and commanded velocity magnitude and direction were given. Intuitively,

the plan-view velocity vector and command used in References 1, 20 and (essentially) 16 appears to be an excellent means for presenting velocity data in analog fashion; pilot comments on formats using this procedure were very favorable in References 1 and 20. In the absence of additional data, therefore, this means of presenting these data is recommended for electronic formats. Since it is velocity with respect to the ground that must be controlled to arrive at the hover point with zero velocity, it is reasonable that this vector present the ground velocity. The reference coordinate system should correspond to that used for range and cross-range data.

It has been advocated earlier that the velocity commands be for airspeed and course prior to the deceleration and ground speed components during the deceleration. For electronic formats, a digital readout of airspeed provides satisfactory information for constant airspeed tracking (Reference 20). To avoid cluttering the display during this portion of the approach, an interesting idea is to show only the lateral ground velocity status and command information -- which corresponds to the course command -- until just before the onset of the commanded deceleration, at which point the longitudinal ground speed status and command information is added. Such an implementation provides an independent warning that the deceleration is about to begin, similar in intent to the ITVIC thrust vector director used in References 1 and 20, which appears to be a necessary display cue (Reference 1). The digital airspeed readout should be kept for the entire approach (Reference 20).

It is generally necessary to have a more sensitive scaling of velocity status and command information for the hover and very low speed part of the approach than can be used for the entire approach. A discrete switch in scaling, under pilot command, should be used (Reference 1); a possibility is to change the scaling along with the coordinate change when the heading-hold yaw augmentation is selected. The hover scalings of Reference 33 are probably appropriate.

6. Control Directors

As was noted earlier, control directors are required in some of the recommended control/display configurations. A variety of implementations of the director symbols and the logic which drives them has been considered; it is important to recognize that incorrect logic or confusing symbols can obviate the usefulness of the directors almost entirely. For this reason, some general precepts which should be followed are summarized below.

All of the control systems that have been recommended employ dual-mode directional augmentation. It is therefore reasonable to eliminate from consideration a control director for the directional controller (Reference 3). For helicopters, three controllers are therefore left: pitch stick, roll stick, and thrust magnitude. The directors should therefore be 3-axis: it has been shown several times that 2-axis directors are not suitable for the helicopter application (e.g. References 9, 14). Each director should also probably be a separate symbol; in Reference 20, an inverted "T" was driven vertically by thrust magnitude commands and laterally by roll stick commands for one of the formats, and was confusing to the pilot. In addition, the location of the directors relative to each other should correspond to the controller positions: one of the other confusing aspects of the inverted "T" was that one symbol commanded two different controllers operated by different hands (Reference 20).

With electromechanical displays, the choice of director symbols is straightforward. The ADI should incorporate two "ILS" needles in the center plus an additional "tab" on the left-hand side; the horizontal needle should present longitudinal stick commands for velocity control, the vertical needle should present lateral stick commands for lateral velocity/position control, and the tab should present thrust magnitude commands for glideslope/altitude control (References 1, 3, 9, 10-14, 15, 20, 28-30, 42). It is incorrect to use altitude command information on the longitudinal stick director because of the "backside" operation for

the majority of the approach (References 1, 9, 10-14, 25). The central location of the needles implies that they be pitch/roll stick directors (central location of controller, right-hand operation), while the left-side tab is the natural thrust magnitude director (left-side location of controller, left-hand operation).

While electronic presentations offer an unlimited variety of director symbols and locations, it is important that the concepts of separate symbols and correct relative location be followed here also. For example, the central location of glideslope brackets in the Phase I CL-84 experiment led to the pilot attempting to control altitude with longitudinal stick rather than thrust magnitude (Reference 16). The sense of the directors and the null point must be unambiguous to the pilot; in Reference 24, the relative motion of the thrust magnitude director (a square) and the longitudinal stick director (the tip of a symbolic flight path) led the pilots to try to null them on each other rather than the reference point. References 1 and 20 adopted the conservative approach in some formats of replicating the needles on the electronic format and using a separate "tab" symbol in the same way that electromechanical instruments are arranged. The only difficulty with this approach was the scan necessary to pick up the thrust magnitude director (Reference 20). A possible correction, which was not examined but might be considered in the future, is to use a "bent bar" for the horizontal needle. The left half of the bar would bend through an angle proportional to the thrust magnitude command, while the vertical displacement of the right half of the bar from the reference index would be the conventional longitudinal stick command. If this concept is not appropriate, the thrust magnitude director should be a separate symbol with fixed index located just inside (to the right of) the rate-of-descent information previously described. The separate longitudinal and lateral needles with a fixed index should be centrally located, preferably near the attitude data.

Regarding the command logic which drives the control directors, several points are apparent from the reviewed programs. First, in essentially all cases, the directors are compensatory (error)

commands, and should have easily apparent nulls (References 1, 9-15, 22, 24, 28-30, 38, 39, 42). Of extreme importance is the blending (summing) of signals which drives the directors. The function of the directors is to achieve acceptable pilot-aircraft response in following the guidance commands and to assist the pilot in stabilizing/controlling the aircraft states; the signals used to drive the directors must be tailored on these bases as well as on the response capabilities of the pilot. Even relatively minor changes in logic can have significant effects. For example, in the VALT experiments a change was made from "zero-reader" logic (feedback of control position to director symbol) to "response command" logic (feedback of only aircraft state errors, References 15 and 29), and apparently improved the suitability of the system. An important design goal is to permit the pilot to act as a pure gain in following the director commands: a requirement for the pilot to generate lead or lag should be eschewed. It was found in Reference 1 that basing the director logic on classical manual control theory (e.g. Reference 65) -- which leads to director response roughly proportional to the integral of control displacement over some frequency range -- was suitable from a pilot capabilities point of view, provided response command rather than zero-reader director characteristics, and led to acceptable guidance-command following for the decelerating task. At the present time, this design methodology appears the most suitable and is recommended; it would be useful, however, to perform additional experimentation comparing other design methodologies.

It is important to note that the use of manual control theory in the control director design process implies that the relative gains of the signals forming the director command vary as a function of aircraft control characteristics. In particular, the control director gains will be different for a rate-damping control system than they are for an attitude command control system. It is also important that considerations such as director response to turbulence be examined during the design process (Reference 3).

7. Additional Information

As is noted in Table 4, some data in addition to the primary flight status and control information discussed above are considered desirable. Most important are engine parameters and wind information. For helicopters, the actual torque and maximum available torque are important monitoring information. In the KLM "reverse T" arrangement, the instrument for torque is to the right of the ADI, below the airspeed indicator (Reference 37); with electromechanical instruments, this place is about the best available after the altitude and IVSI instruments are placed on the left, and engine/rotor RPM can be placed below the torque meter. It is tempting on electronic instruments, however, to have this information on the left, outside of the altitude scale, to correspond to the left hand operation. The difficulty with such an arrangement might be clutter on the left side of the display. In the absence of any real evidence either way (the ITED formats show commanded torque on the left side, Reference 34), it is recommended that this information be given on the left of the altitude scale, but some additional studies are warranted. The torque and maximum-available torque should probably be shown in analog form, with a digital readout for RPM.

It has been emphasized previously that wind direction is an extremely important factor for decelerating instrument approach (Reference 1, 20; Reference 12 did not show a significant effect, but was not a flight experiment). For this reason, a display to the pilot of wind direction would be desirable. However, the best way to present this information (if it is available) is not clear. In Reference 20, a chevron over the heading tape was used to show the relative heading of the wind, but the usefulness of this concept was not really demonstrated. In Reference 16, a marker on the circumference of the landing pad symbol was used to indicate wind direction, but again the demonstrated value was inconclusive (partly because the information was only approximate). The chevron on the heading tape still appears preferable and warrants further investigation.

A final question regards the orientation of the tip-path plane for articulated-rotor helicopters. Reference 4 notes the desire for this information from pilots questioned in a survey. Since the rotor-plane attitude may be quite different than aircraft attitude, it is possible that adding this information can give the pilot additional lead information, although perhaps a "pendulum" effect could result (Reference 34). One way to show such information on an electronic format would be a separate symbol on the tip of the velocity vector, similar in concept to the circle driven by either acceleration or aircraft attitude that was examined in References 33 and 34. Since no experience with display of rotor-plane attitude has been documented, further research is warranted, and no recommendation can be made at this time.

5.0 Concluding Remarks

To summarize the preceding discussions, the following control/display combinations appear, on the basis of the reviewed programs, to be candidates for a satisfactory instrument decelerating approach capability, and warrant comparative investigation:

1. Rate damping in pitch/roll; dual-mode yaw augmentation (sideslip suppression or heading hold); vertical velocity damping augmentation. Integrated electronic display with 3-axis control directors, velocity status and command, position status and command. (Figure 3 gives a possible example).

2. Rate-command-attitude-hold in pitch/roll; same directional as (1); same vertical as (1). Same display as (1).

3. Attitude command in pitch/roll for deceleration and hover, rate-command-attitude-hold for constant (airspeed) acquisition phase; same directional as (1); same vertical as (1). Integrated electronic display with velocity status and command, position status and command (delete control directors from Figure 3, for example).

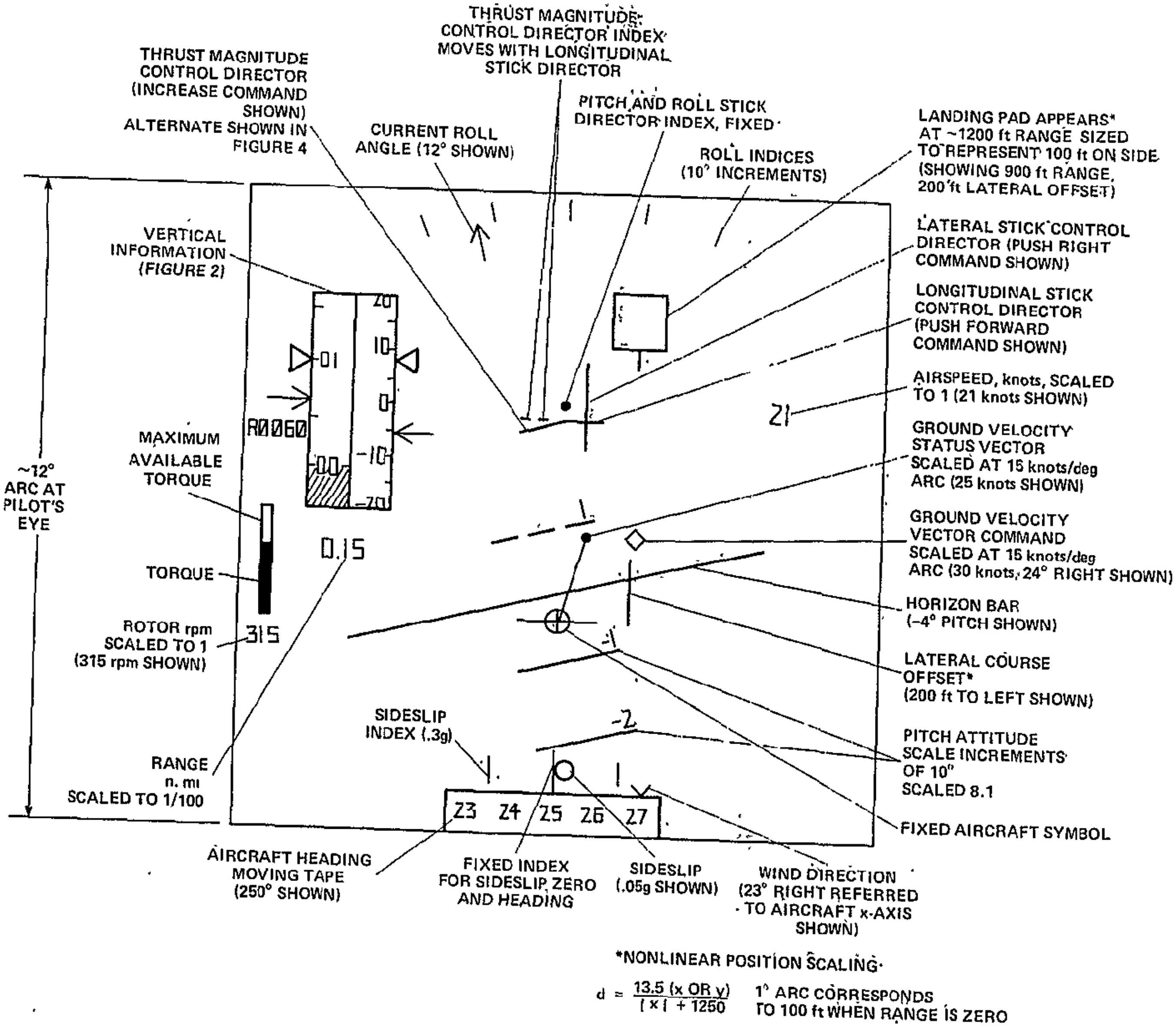


Figure 3.- Possible integrated electronic format incorporating 3-axis control directors.

4. Same attitude as (3); same directional as (1); no vertical. Display as (3) (no control directors).

5. Same attitude; same directional; no vertical. Integrated electronic display with thrust magnitude control director, velocity status and command, position status and command (Figure 4).

6. Same attitude; same directional; no vertical. Separated electromechanical displays; 3-axis control directors on ADI, tape instruments for rate-of-climb and radar altitude (left), lateral velocity and cross-range error (below), longitudinal groundspeed and range (right); "moving map" HSI below ADI (Figure 5).

7. Translational rate command longitudinally; attitude command laterally for deceleration and hover, rate-command-attitude-hold for constant speed; dual-mode directional; vertical velocity command. Integrated electronic format with velocity status and command, position status and command (Figure 3 without control directors).

8. Translational rate command longitudinally and laterally for deceleration, roll rate-command-attitude-hold for constant speed phase; directional sideslip suppression for constant speed, yaw rate-command-heading-hold for deceleration; vertical velocity command. Same electronic format as (7).

9. Same translational, directional, vertical as (8). Separated electromechanical instruments as per (6) without control directors.

It is recommended that these nine suggested control/display configurations be evaluated in both ground and in-flight simulators for decelerating instrument approaches, given a "representative" helicopter model.

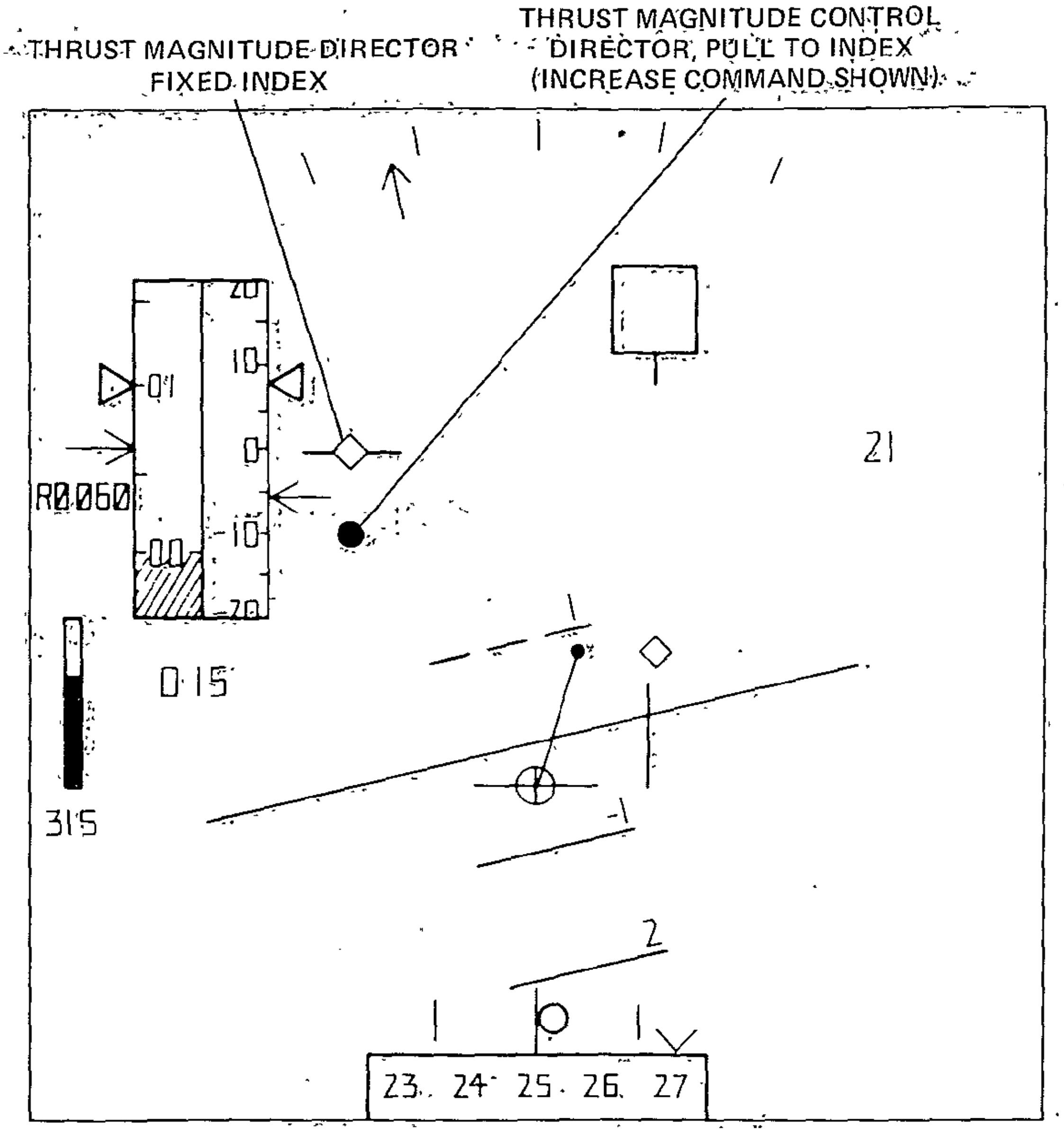


Figure 4.- Possible integrated electronic format incorporating 1-axis control director.

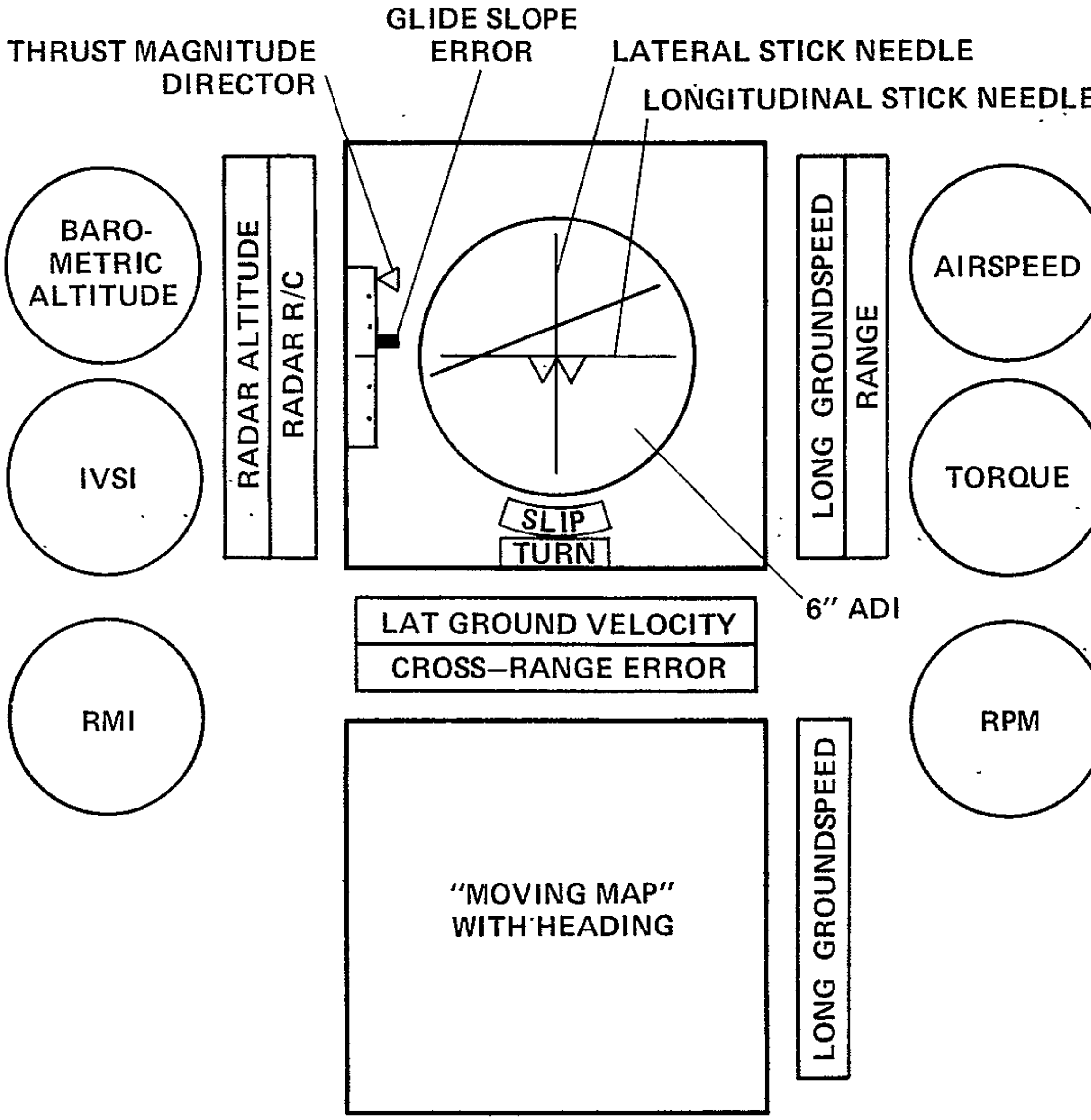


Figure 5.- Possible electromechanical display layout.

Additional research on controller characteristics (forces, sensitivities) is warranted for translational rate control systems; a more general examination of desirable response characteristics for this type of control system is also warranted, as is a comparative investigation with attitude command systems for landing on moving platforms. For the rate, rate-command-attitude-hold, and possibly attitude command control systems, the influence of parametric variations in helicopter aerodynamics, control powers, and SCAS authorities is required. The initial work being conducted jointly by the FAA and NASA for constant speed approaches is a step in the correct direction, and should be extended to decelerating approaches. Additional research examining some of the reasonable alternatives for displaying information on electronic formats, as were reviewed earlier, warrant further investigation.

APPENDIX

This appendix contains an annotated bibliography of the material surveyed for this report. The documents are grouped according to the control system type as discussed in the body of the report.

Group 1: Rate-Damping Control Systems

Clark, W. E., and G. P. Intano: "Helicopter Display Improvement Study". Instrument Flight Center IFC-TN-75-1, May 1975. (Reference 4)

Analysis of questionnaires sent to USAF helicopter pilots concerning helicopter displays. High percentages requested improved course indicator, better location of turn and slip indicator (when no directional augmentation used), the addition of a 3-axis control director, improved attitude indication plus some means of knowing rotor plane attitude. Information in addition to pitch/roll commands and approach status for the flight director: a rising pad, radar attitude, and valid airspeed below 40 knots. Augmentation suggested for below 50 knots steep approaches was yaw first; roll; pitch; collective last. Interesting point for pitch control is that attitude is primary display, rate-of-descent next importance.

Simmons, R. R. et al: "Pilot Opinion of Flight Displays and Monitoring Gauges in the UH-1 Helicopter". USAARL Report 76-18, April 1976.

Questionnaire responses concerning instrument usage in UH-1. Flight instrument rankings (frequency of use) for descent were: airspeed, altimeter, VSI, turn and bank, RMI, ADI, compass. Rankings of "importance" were: airspeed, altimeter, RMI, VSI, ADI, turn and bank, and compass (for VFR only). Strange result is the low ADI ranking even for IFR flight.

Armstrong, G. C. et al: "Pilot Factors for Helicopter Pre-Experimental Phase". IFC-TR-74-2, February 1975. (Reference 5)

Flight tests in TH-1 helicopters, as part of PIFAX-H program, to obtain data about performance/workload during typical IFR maneuvers. Four maneuver profiles used, concentrating on difficult tasks. Current presentation deficiencies noted included: attitude resolution at low speed, lack of low airspeed, rapid oscillations of rate-of-turn, poor location of sideslip, small heading gradations. Standard control system marginal for instrument flight, trim system inadequate. All instrument segments below 70 knots were considered marginal because of flying qualities limitations. Recommend:

- stability augmentation of all axes. Yaw should be done first
- display improvements: omnidirectional airspeed, command steering bars, expanded pitch scale
- turn coordination system, heading hold system
- accurate, well-damped turn indicator

- heading scale closer to pilot's scan center

- "true" trim system

Winter, F. J. Jr.: "Integrated Avionics -- Controls and Displays for Helicopter IFR Operation". SFTE 5th Annual Symposium Proceedings, 7-9 August 1974, pp 2-31 to 2-42. (Reference 6)

Summary of PIFAX-H program first phase, which was collection of data regarding typical IFR maneuvers using conventional instrumentation. Maneuvers tenaed to stress maximum performance profiles (e.g., high rate climbing turns). As a result of pilot ratings for various segments, two recommendations are made:

- yaw augmentation. A system to provide both heading-hold and automatic turn following is required.

- 3-axis flight director

Armstrong, G. C. et al: "Pilot Factors for Helicopter Refined ADI/HSI and Supporting Displays Evaluation". IFC-TR-74-5, June 1975. (Reference 7)

Flight test in TH-1F helicopter, follow-on PIFAX-H work to investigate improved displays (ADI, HSI, IVSI, precision airspeed, and radar altimeter). No quantitative improvements in performance or workload over the baseline TH-1 instruments was found for the selected IFR maneuvers.

ADI: incorporated rate-of-turn and sideslip. Expanded pitch scale.

PAS: J-TEC unit good to zero knots

Qualitative remarks concerning new displays:

- turn and slip to ADI aided coordinated flight, but wanted more sensitive.

- Expanded pitch scale seemed overly sensitive, but was generally an aid for airspeed control

- Pilots wanted pitch, roll, collective commands added to ADI

- Both groundspeed and airspeed desired. PAS inaccurate at low airspeeds

- For hover, onmi-directional airspeed required plus sensitive radar altimeter.

Recommendations were:

- Develop integrated groundspeed/airspeed system
- Develop control augmentation, starting with yaw axis
- Investigate adding pitch, roll, collective commands

Clark, W. E. and G. P. Itano: "Helicopter Yaw Axis Augmentation Investigation". IFR-TR-76-3, March 1976. (Reference 8)

Flight test using TH-1F of yaw augmentation as part of PIFAX-H program. Used "refined" displays from second phase. Yaw augmentation consisted of heading-hold from zero to top speed; above 30 knots, bank inputs of more than 5° give turn following, and heading hold comes back to 2° bank. In flights, required pilots to keep feet off pedals (for some unspecified reason), which was considered distracting. Findings based on incomplete data analysis were:

- Heading tracking better, control activity in pitch axis somewhat reduced.
- Airspeed control no better, pitch attitude performance worse.
- Roll attitude performance better, roll stick activity higher.
- System as flown did not permit small heading changes—(probably combination of feet-on-floor plus switching logic).

Clark, W. E., and G. C. Armstrong: "Three-Cue Helicopter Flight Director Evaluation". USAFIFC-TR-77-3, July 1977. (Reference 9)

Flight test as part of PIFAX-H to look at 3-cue flight director for IFR. Used TH-1F helicopter, but did <u>not</u> include yaw axis augmentation, just basic SAS. Electromechanical ADI with 3-cue control directors (Collins design), glideslope deviation on RHS, rising pad (analog altitude) at bottom, flight path angle on left, digital altitude readout above ADI, integrated sideslip ball, turn rate. Lateral stick director commanded either heading or localizer tracking, longitudinal stick director commanded speed including deceleration (pilot picks final speed, director essentially picks attitude with maximum of 10°), collective director commanded either altitude hold or glide-slope tracking. Capability existed to turn off third director to have 2-axis system, drive horizontal bar either with speed still or with altitude commands. Program flew 90 knots, 3 approaches <u>at constant speed</u> to decision height (no deceleration)

Findings included:

- Preference for 3-cue director, although pilots could do constant speed approaches with 2-cue <u>if</u> speed were on the horizontal bar.

- Pilots could not fly 2-cue with collective commands on the horizontal bar.

- Collective director too sensitive in close.

- Workload too high for single-pilot IFR, more aircraft stability needed.

Recommendations included:

- Tape instruments on periphery for engine and rotor parameters.

- Retrofit aircraft with attitude hold (H-3, H-53) control systems with 3-axis control directors.

- Develop omni-directional airspeed display and sensor.

- Investigate display of rotor plane attitude data

Wolf, J. D., and R. B. Hoppe: "Aircraft Displays for Steep-Angle Approaches". JANAIR Report 681215, July 1970. (Reference 10)

First in a series of studies and ground simulations to develop IFR capability for helicopter descending decelerating approaches. Considered UH-1H (and XV-5) for approaches using constant deceleration to hover. Information requirements developed from questionnaires: pitch and roll attitude, glideslope error, localizer error, vertical velocity, groundspeed, radar altitude, heading, range relative bearing, longitudinal and lateral position error (for hover), barometric altitude, airspeed. Developed 4 "formats": electromechanical ADI/HSI with 3-axis control director, integrated vertical electronic (3-axis directors), and tow plan position electronic formats (course-up and heading-up) with 3-axis directors. In simulations of UH-1 with rate damping augmentation, found little difference in performance among the formats, little difference between straight and parabolic approach profiles, increasing altitude errors with increasing descent angle.

Wolf, J. D., and M. F. Barrett: "IFR Steep-Angle Approach: Effects of System Noise and Aircraft Control-Augmentation Variables". JANAIR Report 700810, April 1971. (Reference 11)

Second in JANAIR series. Part of simulation studies devoted to investigating 4 control systems in combination with the IEVD and heading-up PPI. Control systems were:

- Rate damping SAS
- SAS with heading hold
- Pitch and roll attitude command
- Attitude command with heading hold

Claimed major effect seen was in reduction of control activity for attitude command. SAS with heading hold deemed subjectively "good" for UH-1H.

Toivanen, M. L. et al: "Investigation of Display Requirements for Helicopter IFR Manual Formation Flight Under Various Operational and Environmental Conditions". JANAIR Report 700911, April 1971.

Analyses and fixed-base ground simulation of UH-1H formation flight display requirements (seventh of series to develop requirements). Aircraft was UH-1H with 3-axis SAS added: pitch, roll, yaw rate augmentation. Displays drawn on 19 inch CRT. Center 8 by 8 inches was plan position indicator (PPI), showing leader position, commanded follower position, actual follower position and heading, lateral and longitudinal stick control director, and altitude error off follower with respect to leader. Peripheral displays were rate-of-climb, altitude (both on right hand side), airspeed (left hand side), bearing-distance and attitude (both below). Quickened control director laws used (generally) position, position rate, attitude, attitude rate. Tasks were constant altitude position tracking.

One item looked at was earth (leader) - up versus heading (follower) - up axes for display presentation. No differences found in position tracking performance.

Wolf, J. D. and M. F. Barrett: "IFR Steep Angle Approach: Effects of Wind, System Data-Rate, and Contingency - Event Variables". JANAIR Report 711105, December 1971. (Reference 12)

Simulation study using UH-1H, that concentrated on effects of wind variables for steep IFR decelerating approach. Aircraft had rate-damping-only in pitch, roll, yaw. Examined 6^{o} and 15^{o} straight glideslope, constant .075g deceleration; initial ground velocity of 64 knots for 6^{o}, 47 knots for 15^{o}. Two electronic display formats investigated, one based on integrated vertical information (IEVD) and the other on plan-view information (PPI).

IEVD: Altitude analog tape on left with thrust magnitude control director cursor

- Groundspeed analog tape on right
- IL (box relative to aircraft symbol)
- Plan position error (two trapezoids, one fixed)

- Longitudinal and lateral stick directors
- Heading command cursor, pitch and roll attitude bar
- Sideslip ball (at top)
- Separate display for rate-of-climb (to left)
- Separate display for bearing-distance-heading (BDHI)
- Separate (flashing) symbol for deceleration initiation

PPI: Heading-up reference plan position error plus approach course with glideslope and deceleration markers

- Rate-of-climb, BDHI, and sideslip as with IEVD
- Separate airspeed dial to right, separate ADI below
- Altitude analog tape at left plus altitude error and altitude-rate-error cursors by tape: track altitude error with rate error for vertical command
- Longitudinal and lateral stick directors

Control directors were driven by velocity, attitude and (inside 50 feet) position. Looked at mean winds of 5, 10, 20 knots from 270°, 315°, 360° plus turbulence with equal to 1 1/2 mean wind. Also looked at loss of control director information.

Results included:

- Lateral tracking during deceleration somewhat better with PPI
- 15° approaches less precise than 6°, attributed to less stability of the flight condition used
- Control activity increased with increasing winds/gusts
- No effect of wind direction (surprisingly)
- Control losses occurred with high wind, steeper angle
- IEVD better than PPI when no control directors, but neither acceptable for deceleration or hover when control directors gone.

Wolf, J. D.: "Display and Related System Requirements for IFR Steep Approach: Final Report". JANAIR 711106, January 1972. (Reference 13)

Summary of analyses and ground simulations to provide IFR approach capability for VTOL. Summarizes results documented in three earlier reports. Studies used ground simulations of UH-1 and XV-5, both with 3-axis rate damping stability augmentation; found also that heading hold significantly helped UH-1. List of information requirements (which was used as basis for Lebacqz/Aiken X-22A experiment):

- Pitch/roll attitude, heading
- Vertical and lateral path error (approach), position error (hover)
- Vertical velocity, radar altitude
- Groundspeed and airspeed
- Range
- Relative bearing

Some of the results indicated no increased difficulty in cross-winds, but possible loss of control in gusting headwinds (20-30 knots).

The recommendations for flight investigation include 3-axis control directors, 3-axis rate SAS and possibly heading hold.

Wingert, J. W.: "Application of Steep Angle Approach in an Engineering and Flight Test Program". JANAIR Report 741002, October 1974. (Reference 14)

Modification for flight tests of previous analytic, simulation work on developing flight directors for helicopters steep approaches. Uses electromechanical ADI with 3-cue director. Display system:

- ADI -- pitch/roll attitude, sideslip, turn rate, longitudinal and lateral stick commands, collective command
- HSI -- heading, course command, localizer and glideslope deviation, longitudinal and lateral position deviation in hover
- Altimeter, VSI, low-range airspeed system

Flight director control laws similar in concept to X-22A Task III (Lebacqz/Aiken). Other information deemed essential is pitch, roll, heading, vertical speed, airspeed (pilots also recommended torque indication). For hover, information should be in head-up axes, and should include translational deviation and, if possible, velocities. Flight program designed to look at approach profiles. Minimum time is given by higher initial speeds, which lowers steepness of allowable descent because of autorotation. Found constant deceleration kept aircraft out of "dead-man's zone" more than exponential, even though a harder control task. Note by authors that 2-cue directors shown to be no good for helos.

Niessen, F. R. et al: "The Effect of Variations in Controls and Displays of Helicopters Instrument Approach Capability". NASA TN D-8385, February 1977. (Reference 15)

Flight test using variable-stability CH-46 helicopter. Instrument approaches from 50 knots to hover, 6^{0} glideslope, constant attitude deceleration. Control systems:

- Pitch, roll, yaw rate feedbacks plus lateral accelerometer (Rate SAS)
- Add pitch and roll to first (Attitude SAS)
- High gain attitude augmentation with prefilter "model", dual mode directional (Attitude CAS)

Displays were ADI plus electromechanical moving-map horizontal situation. Two variations:

- Raw localizer and glideslope error data on ADI pointers
- Three axis control directors on ADI pointers

Also had radar altimeter plus rising runway on ADI, control director logic was not varied as function of control system, nor were commands resolved to aircraft axes to permit crabbed approaches.

Pilot evaluations showed "situation" data display not adequate for deceleration to hover regardless of control augmentation. Rate SAS unacceptable: CH-46 with rate damping had real divergence (T to $b \cong 3$ second), led to possible performance with flight director but too high workload. Little difference in ratings or performance between attitude SAS and attitude CAS control systems.

Barrett, R. N. and R. G. White: "The Flight Development of Electronic Displays for V/STOL Approach Guidance". In AGARD-CP-148, May 1974. (Reference 16)

Flight tests of CL-84 and SC-1 with head-up displays, partially instrument approaches. Formats were integrated horizontal-vertical. Both had pitch/roll horizon (with ladder used for CL-84), sideslip at bottom, heading tape at bottom, landing pad and approach course symbol, vertical velocity analog scale on right, digital altitude readout at right, digital airspeed and range, analog longitudinal acceleration on left, "guidance vector" comprised of quickened velocity (ground) information. CL-84 had glideslope brackets in center, SC-1 had commanded vertical velocity shown on vertical velocity scale. CL-84 control system was rate damping pitch, roll, yaw plus a small amount of pitch attitude feedback. SC-1 had attitude command in pitch and roll and turn-following directionally. CL-84 approach profile was instrument approach at 4^{0}, 90 knots to 200 feet AGL level off, initial deceleration on instruments in level flight (constant deceleration) with breakout to visual at approximately 45 knots. SC-1 profile was level deceleration from 120 knots, apparently all visual.

In CL-84, central location of glideslope brackets and separated glideslope/rate-of-descent/altitude data contributed to poor height control. Aircraft stability was also a problem. Height keeping in SC-1 better, the control augmentation was considered mandatory to fly the profile examined on instruments.

Gold, T. and R. M. Walchli: "Head-Up Display for All-Weather Approach and Landing of Tilt-Wing V/STOL Aircraft". AIAA Paper 74-952, August 1974. (Reference 17)

Phase II flight test of CL-84 using different HUD format than RAE Phase I. CL-84 SAS was rate in pitch, roll, yaw plus small pitch attitude feedback. Task was constant speed (40 knots) approach at 6-12 degree glideslopes followed by level deceleration, all under IFR conditions, to hover. Basic precepts of display were 1:1 scaling of all angular analog symbols -- pitch, roll, and heading -- plus 1:1 overlay of superposed runway image on actual runway. Display had two modes: approach and transition. Symbology summary:

- Digital airspeed on left hand side, digital altitude right hand side, analog (thermometer) rate-of-climb right hand side
- 1:1 analog heading pointed on pitch attitude lines plus digital heading readout
- Pitch ladder 1:1, two "lubber-lines" for fuselage reference at -7° plus circles indicating -7° reference for zero pitch attitude. Circles driven by pitch only - not roll
- Glideslope bar (approach mode) with course circle to line up with runway
- Speed error diamond referenced to glideslope bar
- In transition mode, glideslope bar becomes angular deviation from hover point

Display had approximately 12° vertical field-of-view and 15° lateral field-of-view. Lateral in particular caused all sorts of problems with 1:1 scaling precepts used; authors go so far as to state that VTOL operations should be limited to conditions in which less than 7° of crab would exist, which is solely a result of their adherence to 1:1 overlay principle.

Results of flight test included:

- Pilots liked runway image in approach mode, even though overlay errors of $\pm 2^{\circ}$ were typically present and information was gone for crab angles over 10°.
- 1:1 heading pointer bad, couldn't get heading trend from digital readout either
- Pilots wanted lineal indication of errors rather than angular given by glideslope bar
- Glideslope bar useless for crab angles greater than 7°
- Speed error diamond was not needed during constant speed approaches, but was a requirement to perform deceleration (couldn't do deceleration with only deviation bar).

- For transition, display was deficient in pitch attitude and height information. Height control was the biggest problem.

- Digital heading and altitude readouts not good -- wanted to get trend information. The altitude complaint was probably triggered by the VSI signal being poor (laggy), which made pilots want to get rate of descent information elsewhere.

- 1:1 scaling led to symbol overlay clutter with crab angles which was a deficiency.

Walchli, R. M. et al: "Flight Evaluation of a Head-Up Display with Real-World Overlay for Instrument Approach and Landing of V/STOL Aircraft". NATC-TR-SY-23R-75, October 1975. (Reference 18)

Flight test results of a Phase II CL-84 program. See AIAA paper for description of display, task. Report notes difficulty of altitude control, recommends thrust magnitude director, and indicates that workload during transition was unacceptable.

Yiotis, P. et al: "Study of Head-Up Displays for Helicopters/STOL Aircraft". Report 70-1329-00-00 (AD 744334), March 1971. (Reference 19)

Study to define HUD formats and information content for helicopters. (Precursor to many of the concepts investigated in the Phase II CL-84 program.) Claim is that HUD information should enhance precision of visual flight control, help assess visual scenes, assist instrument flight and transition to visual, give information that must be sampled frequently during head-up flight. Champions real-world overlay surrogate images. Proposed approach and landing format includes "ladder" attitude, flight path marker (lateral and longitudinal), analog heading index, digital airspeed (left side), analog altitude scale (right side), deviation bar (glideslope angle error), landing pad symbol. For hover, adds groundspeed analog information (diamond, longitudinally and laterally), apparently drops airspeed. No discussion of control system requirements.

Gold, T. and R. F. Perry: "Visual Requirements Study for Head-Up Displays". JANAIR Report 700407, March 1972.

Simulator study of binocular disparity tolerances in HUD. Some discussion of field-of-view requirements for helicopters--emphasizes real-world overlays. Some of the format concepts (deviation bar, runway overlay) were later applied in CL-84 program.

Lebacqz, J. V. et al: "An Experimental Investigation of Control-Display Requirements for a Jet-Lift VTOL Aircraft in the Terminal Area". Naval Air Development Center Report NADC-76099-60, July 1978. (Reference 20)

Flight test of simulated AV-8B terminal area instrument approaches. Task was 65 knots acquisition of 5^o glideslope, one-step nozzle change to initiate constant attitude deceleration, level-off at 100 feet AGL at approximately 800 feet range-to-go; majority of work done for entire profile on instruments. Five control systems investigated:

- Rate damping pitch and roll plus lateral acceleration, washed-out yaw, and aileron-rudder crossfeed or heading hold.
- Rate-command-attitude-hold (2 levels of feedback) for pitch and roll plus similar 2-mode directional but with higher lateral acceleration feedback.
- Attitude command (3 levels of feedback) for pitch and roll plus the better directional 2-mode system.

A variety of head-up display formats were investigated in combination with these control systems. Velocity-error-command, one-axis, 2-axis, and 3-axis control director information levels were examined for two basic attitude presentations (3:1 and 16:1 scaling of pitch attitude).

Results appeared to indicate that satisfactory ratings could be obtained with the rate-damping SAS without control directors, although the ratings were very susceptible to winds/turbulence. A variety of formats were satisfactory with attitude command augmentation.

Santanelli, A. S., and R. V. Kurowsky: "Evaluation of a Head-Up Display Used as an Aid in Performing Steep-Angle Approaches". ECOM-4185, January 1974. (Reference 21)

Flight test on UH-1 of commercially-available head-up display. Display showed runway (overlay), analog flight path bar, and flight path angle. Approaches of 6^o-9^o constant speed were made VMC using the HUD and compared to simulated instrument (pilot under the hood) approaches using standard cross-pointers--an incredible comparison the reasons for which are not explained. Found approach angle performance better with HUD and claim less workload also, but it was VMC versus IMC after all. Did note problem with FOV in crosswinds.

Santanelli, A., and R. Kurowsky: "Evaluation of Three-Cue Flight Director Systems". ECOM-4385, January 1976. (Reference 22)

Flight test in UH-1 of four commercially available flight director systems, defined as ADI with integrated 3-cue control directors and an HSI. Three of the four were electromechanical, one used electronic ADI (the same as used in Reference 24); one of the electromechanical systems appears to be the one designed on the basis of JANAIR study of Reference 14. Approaches were apparently constant speed at a variety of flight angles. The three electromechanical displays were all considered inadequate because of control director sensitivity and erratic behavior; the EADI format was cluttered when on course.

Winn, A. L. et al: "Instrument Flight Evaluation OH-6A Helicopter, Part I". USAASTA Project 72-06, AD 780016, November 1973. (Reference 23)

Flight evaluation of OH-6A instrument flight capability with basic instruments and the electronic 3-axis flight director display. Basic OH-6A instruments had to be augmented by IVSI and turn-and-slip indicator. Lack of good force-feel characteristics longitudinally and laterally and difficulty in establishing trim below 65 knots (essentially neutral stability w.r.t. speed) caused objectionably high workload, aircraft was judged unacceptable for instrument flight with the basic instruments. In addition, the ADI was unacceptable because of low sensitivity. Adding the electronic ADI with 3-axis directors significantly improved IFR capability, although director commands were too sensitive, heading symbology was poor. Flying qualities of basic OH-6A made it still unsatisfactory.

Griffith, W. E. II et al: "Flight Evaluation OH-6A Helicopter Kaiser FP-50B Flight Director System, Part II". USAASTA Project 72-06, AD 781990, February 1974. (Reference 24)

Follow-on flight tests to determine operational suitability of OH-6A with Kaiser flight director display (FDS). FDS is CRT with artificial horizon, 3-cue director ("flight path" for pitch-roll plus square for collective), centered at horizon. Compared FDS to basic IFR for several IFR flight segments. IFR descents were performed at speeds 50-90 KIAS and 500-1400 fpm descent; ILS approaches at 70, 80, 90 KIAS and 2.5 degrees. FDS uses collective for rate-of-descent control and longitudinal stick for airspeed control; the lateral "director" is really just heading error, not a steering command.

In IFR descent, FDS gave much better workload-performance indices than basic IFR. Collective workload increased somewhat with increasing rate-of-descent, but less than basic IFR. Airspeed control workload independent of rate-of-descent with FDS, higher for higher R/D with basic IFR. FDS included flare logic initiating at 300 feet (steep descent) or 200 feet (normal descent) that decelerated and levelled-off aircraft smoothly to 30 KIAS, 15 feet AGL; authors recommend 45 KIAS, 25 feet AGL instead because of flight safety and airspeed sensor limitations.

ILS approaches were considered satisfactory with the FDS (PR=3), with significantly reduced pilot effort over the basic IFR package. Asymptoric capture of localizer considered undesireable, terminated approaches with aircraft 150 feet laterally off centerline undesireable. Authors state that no minimum decision height would be required with the FDS.

Undesirable features of display:

- Pitch and collective commands were supposed to be nulled at horizon, but design of format tended to make pilots try to null them on each other.
- Could not initiate descent until airspeed following achieved.
- Recommended decreasing sensitivities of commands.
- Recommended a steering command.

Benson, T. P., and J. R. Smith: "Instrument Flight Evaluation OH-58A Helicopter". USAASTA Project No. 72-01, September 1972. (Reference 25)

Flight evaluation of OH-58A instrument flight capability with basic instruments and with electromechanical 2-axis flight director. Basic OH-58A instruments had to be augmented by IVSI. With basic instruments, aircraft unacceptable for IFR because of excessive pilot workload, probably exaggerated by poor control centering and inadequate lateral-directional damping. With flight director, pitch and roll stick commands were provided but <u>no</u> collective command: philosophy was <u>front-side</u> -- use pitch for altitude control. Pilots could not perform ILS approaches satisfactorily with the 2-cue director.

Bailes, E. E. et al: "Handling Qualities Evaluation OH-58A Helicopter Incorporating a Mini-Stab 3-Axis Stability Augmentation System". USAAEFA Project No. 74-23, February 1975. (Reference 26)

Flight test of OH-58A (Jet Ranger) with SFENA add-on SAS. SAS has angular rate damping plus integrators in pitch, roll, yaw to give rate-command-attitude-hold in all three axes. Attitude retention switched out for control inputs greater than 2% of full scale, switched back in when angular rate becomes less than 1-1/2 deg/sec. SAS greatly improved OH-58A handling qualities, particularly for lateral-directional and improved precision hover characteristics plus terrain following and bob-up/pop-up tasks.

Skinner, G. L. et al: "Instrument Flight Evaluation of AH-1G Helicopter". USAAEFA Project No. 72-29, AD A026633, July 1975. (Reference 27)

Flight evaluation to determine operational IFR suitability. SCAS was pitch, roll, yaw rate feedback, 25% authority, no stabilizer bar. Conventional instrumentation. Aircraft had good (PR < 3 1/2) flying qualities VFR, particularly longitudinally: good attitude-velocity relationship, "dead-beat" stick response SCAS ON and OFF from 75 to 100 knots. Roll satisfactory SCAS ON, directional damping only "adequate" ($\zeta \cong .2$ to $.3$) up to 120 knots SCAS-ON, bad above. Claim is that precision-workload measures were five times better than OH-6A -- much better inherent flying qualities. IFR steep descents flown at 80 knots, 1450 fpm (10^{o}); 10^{o} about maximum before vortex ring or autorotation. Steep descents not recommended SCAS-OFF, although in general only effect of SCAS is directional. IFR approaches flown at 100 knots, 500 fpm (23^{o}), rated satisfactory (PR=3).

Simon, D. R., and J. C. Savage: "Flight Test of the Aerospatiale SA-342 Helicopter". USAAMRDL-TR-75-44, August 1975.

Flight test of Gazelle with improved fan-in-fin. No IFR work done. Important point is excellent flying qualities enhanced by excellent speed stability and turn-following in cruise, pointing out why this machine is IFR-certified single-pilot: minimal attention to speed control and heading required.

Ammerman, L. R.: "Evaluation of an Integrated Electronic Instrument Display for Helicopter Hover Operations using a Six-Degree-of-Freedom Fixed-Base Simulation". AD A010-834, March 1975.

Fixed-base simulation of SH-2F with one electronic display format. Display had altitude, vertical rate, airspeed, attitude, rate-of-turn, sideslip, heading, horizontal position error "cross". Task initiated at 500 feet AGL, 70 knots, 2 nm, fly to hover at 40 feet AGL, cross centered. Of 5 evaluation pilots, 4 could not perform task because of aircraft stability problems. No stability augmentation system was included in the simulation (apparently), even the H-2 base. Attitude presentation on display was also considered poor.

Duffy, T. W.: "An Analysis of the Effect of a Flight Director on Pilot Performance in a Helicopter Hovering Task". Naval Postgraduate School Masters Thesis, March 1976.

Fixed-base ground simulation of UH-1H (longitudinal only) with two displays. Task was precision hover. Simulation model had Mq representative of pitch-rate SAS. Displays gave longitudinal position relative to pad and altitude: no velocity information. Flight director (longitudinal stick only) driven by $\dot{X}$, X, θ, q. Performance both longitudinally and vertically improved with flight director.

GROUP 2: ATTITUDE AUGMENTATION/COMMAND CONTROL SYSTEMS

Rempfer, P. S. et al: "Fixed-Base Simulation Evaluation of Various Low-Visibility Landing Systems for Helicopters". NASA TN D-5913, March 1971. (Reference 28)

Ground simulation of CH-46. Approach task was 42 knots along 6°, level off, deceleration (constant) to 10 knots. Electromechanical ADI with 3-axis directors. Looked at both 3-axis directors and raw ILS data for these control systems:

- pitch/roll attitude command, dual mode yaw
- above plus vertical augmentation with altitude hold
- longitudinal velocity commanded by pitch stick, course by lateral stick, vertical and directional as in second system

Found that first control system operationally unacceptable even with control directors for full task, other two acceptable. Hence, claim vertical augmentation essential.

Kelly, J. R. et al: "Flight Investigations of Manual and Automatic VTOL Decelerating Instrument Approaches and Landings". NASA TN D-7524, July 1974. (Reference 29)

Flight test using CH-46. Task was decelerating instrument approach from 45 knots to hover along 6° or 15° straight glideslopes. Previous work looked at exponential, constant deceleration, and constant attitude deceleration profiles -- constant attitude found to be best. Control system was high gain prefiltered attitude command in pitch and roll, dual mode (from following or heading hold) directional. Display was electromechanical ADI with 3-axis control directors and electromechanical moving map. Concluded that excellent performance attainable but pilot workload operationally unacceptable. Note that this configuration later received rating of satisfactory (PR=3) in Reference 15.

Kelly, J. R. et al: "Flight Investigation of a Vertical-Velocity Command System for VTOL Aircraft". NASA TN D-8480, July 1977. (Reference 30)

Flight test with CH-46. Added vertical damping, vertical-rate-altitude-hold to high gain attitude systems previously investigated. Same 3-axis control director ADI and moving map. Added commanded vertical speed dial to left, still had IVSI on right. Did approaches at 10°, initial speed 65, constant attitude deceleration to hover on instruments. In VFR trials, two unexpected

problems: pilots wanted to flare even though system was earth-referenced, and feedbacks produced torque deviations which made pilots nervous (power limiting needed). For IMC, showed definite glideslope tracking improvement.

Born, G. J. et al: "Final Report -- Flight Path Control and Performance Analysis. Final Report -- Integrated Display". ECOM-0161-72-F, July 1974. (Reference 31)

Analyses and ground simulation to develop Superimposed-Integrated Trajectory Error Display (S-ITED). Aircraft used as model is CH-53 with SAS and ASE (attitude command pitch and roll, heading hold, altitude hold). Final version assuming ground referenced position data has following characteristics:

- Fixed aircraft symbol with rotating tail to show heading. Intermediate form had fixed landing pad, moving aircraft, but fixed aircraft finally picked.

- Moving hover point cross in "approach-course-up" reference frame (not aircraft-heading-up).

- Translational velocity vector (horizontal) in approach-course-up frame.

- Altitude and rate-of-climb plus torque on left hand side in analog form plus scale.

- Airspeed analog scale on right hand side.

- Turn and slip indicator at top center.

- Horizon light, broken out of middle third of display, with pitch and bank references on right hand side.

In developing this information content, authors found explicit display of horizontal translational velocities essential for hover accuracy even when display superimposed on video image.

Tsoubanos, C., and R. Covington: "Preflight Test Simulation of Superimposed Integrated Trajectory Error Displays". ECOM-4184, January 1974. (Reference 32)

Ground simulation investigation of hover accuracies using video image plus superimposed analog symbology. Simulated aircraft was CH-53; one pilot flew without ASE (adds heading and altitude hold to SAS), rest with ASE. Ten "formats" investigated: two with no symbology, four with no horizontal ground reference data on symbology, four with ground reference data (one of which had no video). None had control directors. Task started with hover at 75 feet AGL, 500 feet range, pilot flew to landing zone.

Results were:

- ASE required. Without it, hover dispersions of less than 25 feet could not be achieved regardless of display.
- Retaining the electromechanical ADI attitude data was required.
- Formats without ground-referenced position error data superimposed did not enhance hover accuracy, even when translational velocity was explicitly shown.
- Formats with ground-referenced position error data superimposed (all of which also had translational velocity) gave good position tracking.
- Full information format without TV view gave comparable performance to those with TV view.
- Good performance also achieved if altitude, rate-of-turn, sideslip, rate-of-climb, attitude removed from superimposed data and pilot required to scan basic instruments for them.

Authors recommend for flight investigation (with ASE):

- Full ground-referenced format and TV.
- Full ground-referenced format without TV.
- Simplified ground-referenced format (no attitude, etc.) and TV.
- Marker-star format (no ground reference) with velocity and TV.

Tsoubanos, C. M.: "An Investigation of Displayed Ground Referenced Position, Velocity, and Acceleration for Precision Hover". ECOM-4334, July 1975. (Reference 33)

Ground Simulator Study of superimposed format on video image for hover task. Format was full ITED from previous work with additional circle driven by horizontal accelerations or aircraft attitudes. Three control systems:

- Full ASE as before: altitude hold, heading hold, attitude command in pitch and roll.
- Rate SAS: the ASE with the two attitude feedback loops (pitch and roll) opened, still had heading and altitude hold.

- HAS: Added feedbacks of u and v to the pitch and roll attitude command loops of the ASE, respectively, to becone a quasi velocity-command system.

Only display variation was the sensitivities of position, velocity, and acceleration data. Task was initiated at 100 feet AGL, 300 feet range, hover; pilot flew to 50 feet AGL over hover spot, hovered for two minutes, went to second spot and repeated. Results were:

- SAS could be stabilized if acceleration data given. Required more pilot training than other systems, dispersions were approximately X times greater but still less than previous work.

- ASE and HAS were approximately equivalent in performance, although HAS a little better.

- Using attitudes instead of acceleration to drive circle made it less jerky but some complaints of "sluggishness".

Author recommended flight investigation using ITED plus acceleration with both the ASE and SAS systems.

Keane, W. P. et al: "A Versatile Display System for NOE Operation". American Helicopter Society Paper 77.33-24, May 1977. (Reference 34)

Summary of design of superimposed symbology for NOE using FLIR plus ITED principles. Design constraints were that all symbols (including position and velocity) be driven by on-board sensors. Four modes designed for AAH type aircraft: cruise, transition/NOE, hover, and bob-up. All modes contain:

- Airspeed tape on right-hand side (assumes sensor good to zero).

- Heading type and command at top.

- Radar altitude thermometer on left-hand side.

- Engine torque and scale on left-hand side.

- <u>No</u> sideslip or turn rate data.

Cruise adds:

- Nose of aircraft symbol (to take account of FLIR depression angles).

- Aircraft symbol plus pitch/roll.

Transition/NOE adds:

- Fixed helicopter symbol.
- NO attitude information.
- Horizontal translational velocity.
- Translational acceleration circle. While previous work claimed this symbol assists stabilization, this reference admits destabilizing tendency. Claims the translational acceleration shown is not body-accelerometer output. Now drive the "acceleration" circle with washed-out pitch and roll attitude.

Hover adds to NOE:

- Square fixed inside helo symbol, driven by nothing.

Bob-up adds:

- Square driven by integral of velocity data.
- Heading deviation from initial select.

No simulation results reported, but authors state flight tests to be conducted.

Snyder, W. J., and M. B. Schoultz: "Civil Helicopter Flight Research". AIAA Paper No. 76-896, Aircraft Systems and Technology Meeting, September 1976. (Reference 35)

Summary of NASA CH-53 flight activities, part of which included brief examination of IFR terminal area operations with three different SAS implementations:

- SAS -- ON
- Yaw and altitude -- OFF
- All SAS -- OFF

Unfortunately, "SAS" isn't described (but see other CH-53 documents). Pilots could do IFR approaches and decelerate to 20-30 knots SAS -- ON (PR=2, 3), but could not do it SAS -- OFF; apparently could not transition all the way to hover regardless of control augmentation with the instrument complement used. Displays not defined either, nor appropriate references given.

Moen, G. C., and K. R. Yenni: "Simulation and Flight Studies of an Approach Profile Indicator for VTOL Aircraft". NASA TN D-8051, November 1975. (Reference 36)

Ground simulation and flight test of approach profile indicator and closed-circuit TV picture for helicopter approaches. Interesting concept of augmenting visual electronic display with electromechanical instruments. Display was CRT showing just the visual scene; underneath were five tape meters showing: cross-range error, rate-of-climb error, altitude, range, groundspeed. The latter three were situation information, but scales were selected so that keeping altitude and groundspeed needles aligned with range needles meant following the prescribed descending decelerating forfiles. Rate-of-climb error tracked altitude if on profile, led or lagged to indicate departure. Aircraft (and simulation) was SH-3A with ASE (attitude command in pitch and roll, heading hold but no altitude hold). The task was a descending (6° glideslope) decelerating approach from 80 KIAS, 800 feet AGL (900 in simulator) to hover at 40 feet AGL with some level-off at end. Deceleration profiles were computed from:

$$\dot{x} = a\,(x + b)^{1/2} + c; \qquad \ddot{x} = (a^2/2)\,[1 - b^{1/2}/(x + b)^{1/2}]$$

Claim is that this profile is similar to constant attitude deceleration. The "best" profile (from ground simulation) was one commanding 110 knots at 10,000 feet range; note, however, that task was initiated at 80 KIAS, which pilot would hold until range marker came down to groundspeed marker. Findings include:

- API did not improve cross-track performance: pilots relied on TV picture (both simulator and aircraft).
- API significantly reduced workload, and significantly enhanced repeatability.
- Groundspeed profile used in flight was based on 100 knots initial speed. Pilots said strongly it was too slow, came to almost hover too far from pad.

van der Harten, R. J.: "Some Aspects of Instrument Flight". Vertiflite, November-December 1972. (Reference 37)

Summary of operational aspects of KLM oil rig operations. Use S-61 helicopters, which have attitude command, pitch and roll, yaw-heading hold, and altitude hold. Do constant speed approaches with limits: 150 feet cloud, 800 meter RVR. Developed "close-scan" arrangement for conventional electromechanical instruments: ADI with ILS winters, airspeed to right, radar altitude to left, IVSI below radar altitude, HSI and/or radar below ADI, torque and rotor RPM below airspeed. Uses six-inch ADI for more precise attitude control. Approach speed is 70 knots, no instrument deceleration.

van der Harten, R. J., and P. G. Cooper: "An Electronic Integrated Pilot Display is Evaluated in North Sea Operations". AHS preprint 1021, May 1976. (Reference 38)

Flight evaluation of integrated electronic display in S-61 for North Sea IFR. Features of EADI including 3-axis control director:

- IVSI on right side (!), even though KLM puts instrument on left.
- Rising runway at bottom for last 500 feet altitude.
- Cyclic commands are runway in sky: fly tip of path to center dot.
- Collective director is square referenced to horizon (fly from)
- Failure data shown on left.

Not using for decelerating approaches yet. Some results:

- Need range
- Turn and slip too small
- Pitch scaling too sensitive

Cooper, P. G.: "A Flight Director/FLIR Helicopter Night Landing System". American Helicopter Society Paper 77.33-23, May 1977. (Reference 39)

Flight tests in CH-53 of FLIR plus superimposed display imagery. Night approaches using no ground guidance data. Display uses line-of-sight principle: pilot selects desired approach angle, waits until FLIR image of landing area bisects symbol, then descends following collective and longitudinal/lateral stick directors to decision height; deceleration programmed as function of altitude. Display slows pitch (sort of) and roll via the approach angle line: no pitch scale or reference other than FLIR horizon, however. One symbol commands collective and lateral stick (up-down and left-right), separate symbol longitudinal stick (up-down), all referenced to approach angle line. Presumably, CH-53 SAS plus ASE was active (attitude command pitch and roll, heading and altitude hold). Flew angles of 3°, 6°, 9°, 12°; initial velocity not given. Results:

- Successful approaches to 150 feet AGL, 40 knots, 300 fpm.
- Low training time
- Collective/lateral stick symbol obscured landing area.

Bailes, E. E. et al: "Instrument Flight-Rules Capability Evaluation CH-54B (TARHE) Helicopter". USA ASTA Project No. 71-01, December 1972. (Reference 40)

Operational flight evaluation of CH-54B instrument capability. Control system is rate-command-attitude-hold in pitch and roll, has heading hold and altitude hold also. Electromechanical "conventional" instruments with altitude information on right side (separate from/slip indicator also). Did not do instrument approach, but did work at instrument hover, climb, cruise. Even so, claimed excellent controllability would make aircraft acceptable for IFR missions.

Keyser, G. L. et al: "Navy Evaluation of Automatic Hover Coupler in UN-1N Helicopter Final Report". NATC-FT-84R-74, November 1974. (Reference 41)

Flight evaluation of UH-1N with AFCS and hover coupler. Report on AFCS not available -- inferences on it drawn from this report. AFCS significantly improved flying qualities over basic aircraft. AFCS had two parts: a rate-damping (pitch, roll, yaw) SAS and attitude/altitude retention; hence essentially rate-command-attitude-hold with no vertical damping. Neutral speed stability at 90-110knots was a deficiency. Lack of turn following was a deficiency. Heading hold considered excellent, enhancing feature. Displays were electromechanical, including hover indicator, which was too far outside scan and too insensitive (unacceptable).

Boriss, R., and W. Sabey: "Integration of 4-Cue Flight Director and 4-axis Autopilot with MLS for Cat III Helicopter IFR". Professional Pilot, March 1975. (Reference 42)

Reprint of paper: report on subject not located. Flight tests with UH-1 equipped with Sperry automatic flight control system and flight director. Director adds fourth cue for rudder, uses electromechanical ADI and HSI. Also shows glideslope deviation, rising pad, and turn/slip in ADI. Apparently flew with attitude command, decelerating approaches from 80 knots on 6^{o} glideslope. Claim is satisfactory performance.

Moxem, L. R.: "Westland Design Philosophy on the Lynx for Instrument and All-Weather Flying". Aeronautical Journal, May 1974.

Description of Lynx systems to enable all-weather operations. Control system is attitude command for pitch, attitude command for roll up to /^{o} bank, then rate damping, heading hold in yaw. Sensors include ground velocity and true air velocity from Dopplers, so wind can be calculated. Use electromechanical flight instruments.

Levitt, L. H. et al: "Study of a Hovering Vehicle Versatile Automatic Control System (HOVVAC) for Advanced Helicopter and Vertical

Takeoff and Land (VTOL) Naval Aircraft". Volumes I and II, LJ-1253-0890, August 1968. (Reference 43)

Detailed design study of HOVVAC concepts. Application to CH-53 and XC-142 stressed. For hover, system provides attitude command in pitch and roll ($_n$ = 4 rad/sec,   = 0.7) with a 5 rad/sec first order "prefilter" on the stick command. Vertical is augmented integral-of-vertical-acceleration (no altitude hold), directional is rate damping (no washout) only. The pitch/roll design was compared with three others on basis such as redundancy requirements, authority usage, complexity, etc., and picked as preferable over one using high rate damping and feed-forward lead (other two were slower responding designs). System has low-rate automatic parallel trim to keep series servos centered. Found that series servo authority must be at least 50% for this concept. System switches to "transition" mode between 40 and 60 knots airspeed: pitch and roll new rate-command-attitude-hold, <u>no</u> vertical augmentation, directional provides turn-following through washed-out yaw rate, roll-rate-to-rudder, and lateral acceleration. Switching logic based on change from frontside to backside control technique.

Miller, R. J.: "Hovering Vehicle Versatile Automatic Control (HOVVAC) Development Program Phase II". AD 503872, August 1969.

Description of HOVVAC hardware design and construction.

Guyther, J. R. et al: "Investigation of Automatic Coupled Curved Approaches". NATC-SA-11R-75, June 1975. (Reference 44)

Flight tests using UH-1N with HOVVAC (and fixed wing CTOL aircraft) to do coupled approaches with SPN-42 radar; flew hypercolic and circular curved (in azimuth) paths. For UH-1N, claim additional work to define "optimal" paths and display algorithms required.

Huff, R. W. et al: "National Microwave Landing System (MLS) Supporting Development". NATC-RW-48R-76, December 1976. (Reference 45)

Flight tests of UH-1N with HOVVAC system to look at coupled approaches with MLS. No separate document on HOVVAC flight test alone located: part of this effort was to debug HOVVAC. Flew approaches to 50 feet AGL and 40 knots, glideslope up to 9^o, including curved paths. Initial speed was approximately 100 knots, used 2 feet/sec^2 constant deceleration. HOVVAC SAS gave attitude command in pitch/roll below 50 knots, rate-command-attitude-hold above, turn coordination (lateral acceleration) above 50-60 knots, yaw rate damping. Optional ASE provided pitch, roll, yaw attitude hold; heading hold could also be selected separately. Use electromechanical ADI with 3-pointers driven by status information as mointor: center needles had localizer and glideslope error, left pointer had airspeed error. Some straight-in manual approaches (to 40 knots) were flown with this display.

Group 3: Velocity Augmentation/Command Control Systems

CAE Electronics Ltd. et al: "Tactical Aircraft Guidance System Advanced Development Program Flight Test Phase Report. Volumes I and II". USAAMRDL-TR-73-89 (A and B), April 1974. (Reference 46)

Description and flight test results of TAGS control system implemented in CH-47 helicopter. Complex stability and control augmentation to achieve decoupled control of the three translational velocities plus aircraft reading, implemented in a triplex digital FBW mechanization. No simulated instrument work done in the developmental flight tests. Aircraft used three-axis side-arm controller for longitudinal and lateral velocity plus turn-rate control; vertical velocity controller was like collective stick. No independent control of pitch or roll attitude was provided except when in ground contact (simultaneous fore and aft wheel contact).

Longitudinal: Fairly high feedbacks of pitch rate, attitude, and blended ground/airspeed plus 3rd order shaping prefilter. In addition, crossfeed terms to assist turning, altitude hold. Speed commanded by fore-aft translation of SAC: position of SAC uniquely determined velocity (no spring gradient, but damping gradient to provide force-commanded-acceleration gradient).

Lateral: Medium feedbacks of roll rate, attitude, and hybrid groundspeed/air velocity plus 1st order shaping prefilter. Cross feed terms also, lateral velocity commanded by lateral (angular) displacement of SAC (maximum ± 35 knots) with heading held constant, position uniquely determined velocity. Lateral velocity time constant of 3.4 seconds picked as compromise between hover and forward flight.

Directional: Feedbacks of yaw rate and heading, second order command filtering. Cross feed terms also. Command is heading rate via commanded bank angle for forward flight. Commanded by twisting SAC controller.

Vertical: Feedback of rate-of-climb through proportional plus integral. Feed forwards to drive essentially an acceleration system with command shaping to make rate, time constant of 1.38 seconds.

Flight test results showed excellent vertical control, some problems with precision hover longitudinal control caused in part by the SAC, difficulties with long-term lateral velocity control in hover and overshoots in forward flight, excellent turn coordination, excellent heading hold. Control system considered good for precise steady or low frequency control changes; multiaxis control and/or maneuvering judged more difficult than conventional control system. Felt that improved speed stability would enhance vertical landing capability on instruments. Simultaneous commands inhibited by SAC.

Bryant, W. B. et al: "VTOL Advanced Flight Control System Studies for All-Weather Flight, Volumes I and II". USAAMRDL-TR-75-13 (A and B), July 1975. (Reference 47)

Follow-on TAGS analysis and flight test in CH-47. Several changes to system made; important flying qualities one concerned longitudinal side-arm controller (SAC) characteristics for precision hover: added centering spring (5 pounds/inch) and reduced sensitivity from 40 knots/inch to 15 knots/inch (looked at 5 knots/inch also, no improvement but authors felt slow longitudinal velocity response time was responsible because HLH had shown improvement with lower sensitivity). Changes, particularly centering spring, contributed significantly to precision hover.

Also flight tested simulated instrument approaches with TAGS control system by generating straight approach paths with on-board INS equipment. Majority of approaches at 6° and 10°, although looked at angles up to 90° (!). Displays were:

(1) ADI with raw deviation of glideslope, localizer on cross pointers.

(2) Tape hybrid longitudinal speed and commanded speed (to right of ADI), tape hybrid lateral speed and commanded speed (below ADI), tape hybrid vertical speed and commanded speed (to left of ADI).

(3) Tape distance-to-go (to right of hybrid longitudinal speed).

(4) Horizontal position grid on "projected map", moving.

Approaches included "open-loop" decelerations to hover, initiated at 500 feet range. Approach speed was set to give 500 fpm descent; hence, 6° was approximately 45 knots, 10° was approximately 30 knots. Pilots could perform entire "hooded" approaches to hover. The longitudinal centering spring on the SAC was felt to improve controllability during approaches. Pilots felt need for accurate range-to-go data (had drift problems with INS) plus range to glidepath interrupt at the approach altitude. One pilot noted that 3-cue directors are generally recognized as being required for helicopters, but that TAGS requires no attention to airspeed and attitude control and hence the two cues (raw deviation data) were adequate.

Merrick, V. K.: "Study of the Application of an Implicit Model-Following Flight Controller to Lift-Fan VTOL Aircraft". NASA Technical Paper 1040, November 1977. (Reference 48)

Analysis and ground simulation of decoupled velocity control system and electronic display for IFR approach. Control system as implemented assumed independent control of all six-degrees of freedom; design predicted upon feedback of accelerations, which may not be practical in real-world situation.

Pitch: attitude command (2 rad/sec)

Roll: attitude command for hover (2 rad/sec), rate-command-attitude hold for forward flight. Option was lateral-velocity command in hover (1.25 rad/sec).

Yaw: RCAH for hover, rate command or sideslip command in forward flight.

V_x: Either acceleration or velocity command through thumbwheel or coolie hat (1.25 rad/sec).

V_y: Velocity command for hover through coolie hat (1.25 rad/sec).

V_z: Velocity command, power lever (1.25 rad/sec).

Used head-down integrated (horizontal-vertical) CRT display. Very complicated format.

- Actual $\dot{h}$, commanded-by-pilot $\dot{h}$, flight director $\dot{h}$ command, all on right side of display.
- Actual V_x (or $\ddot{V}_x$), commanded-by-pilot V_x (or $\ddot{V}_x$), flight director V_x (or V_x) command, all on left side of display
- Pitch trim command and pitch attitude scale
- Roll attitude (broken ladder scale) and flight director lateral central command
- Landing pad symbol (range and crossrange status)
- "Inertial" flight path (vertical frame)
- Digital readouts of acceleration, range, laterial deviation, and altitude

Both straight and curved approach profiles examined. Curved approaches required constant horizontal deceleration at constant rate-of-descent followed by constant vertical deceleration also; straight were constant deceleration. Approaches were flown IFR to hover. Results were:

- Pilot preference for translational rate command being implemented through attitude rather than thrust deflection in hover, particularly laterally (ride qualities problem). IFR approaches used thrust deflection, however.
- Preferred acceleration command over velocity command longitudinally for approaches.

- Preferred straight approaches to curved because of lower descent rate near the ground. Preferred to initiate a flare near ground prior to hover rather than straight in.

- Digital information hard to read.

- Rising pad (analog altitude) information should be added.

- Touchdown square should rotate with aircraft heading (heading up axes)

- Should put vertical velocity information on left, longitudinal on right

- Major difficulty in VTOL approaches was switching from acceleration to velocity command. Pilot could do, but further improvement required.

Corliss, L. D., and D. C. Dugan: "A VTOL Translational Rate Control System Study on a Six-Degrees-of-Freedom Motion Simulator". NASA TM X-62,194, October 1972 (Reference 59).

Moving-base simulator investigation of translational velocity control system parameters for aircraft which achieve control through attitude changes. VFR conditions, no turbulence or wind. Linearized equations for V_x and V_y of form:

$$gT_\delta = (S^3 + K\,_0S^2 + K\,_0{}^2S + \omega_0{}^3)\ V$$

K is "damping" term: used K=2 for Butterworth form, K = 3 for finomial form. Major variables were T_δ and ω_0, plus limited control power look. Assumed control powers of 1.4 rad/sec^2 in roll, 0.7 rad/sec^2 in pitch, although controllers not limited (hence could command more than available depending on control sensitivity), saturation ratio defined as SR = command/available.

- Binomial form found preferable to Butterworth form because of higher damping.

- Velocity sensitivity ($T_V = {}^{gT}/\omega_0{}^3$) found "optimum" at ≅ 5 feet/second/inch for station keeping, ≅10 feet/second/inch for rapid maneuvers.

- Range of good ω_0 was ≅ 1.5 → 2.5 rad/sec. Range of good T was ≅ 0.6 → 1.5 rad/sec^2/inch. Overall "optimum" around ω_0 = 2.0, T_δ = 1.0 (T_V ≅ 5).

- The SR was more than 3 for most of the satisfactorily rated configurations. Limiting available control power showed degradation in pilot rating below ≅ 1.0 for roll (no pitch data given) at SR ≅ 7. Comparison with previous work for acceleration, rate, and attitude angular systems appeared to show somewhat less control power required for translational rate system.

Group 4: ADDITIONAL STUDIES/PROGRAMS

Moen, G. C. et al: "A Parametric Analysis of Visual Approaches for Helicopters". NASA TN-D8275, December 1976. (Reference 50)

Flight investigation to parameterize visual approach profiles for helicopters. Four (4) helicopter types, 236 approaches initiated at 50, 80, 100 knots, differing altitudes. Altitude profiles initially concave down to straight line segment (6.5 to 12°) followed by concave up starting at range of approximately 1000 feet. Peak deceleration generally at approximately 200 feet range, maximum pitch "workload" during final 400 feet. Deceleration usually started around 2800 feet range (the number used for empirical fits) while on straight line segment. Empirical fit to velocity data is:

$$\ddot{X} = \frac{K\dot{X}^2}{X^n} \qquad \begin{array}{l} n \cong 1.7 \text{ for 50 kt initial} \\ \;\;\, \cong 1.4 \text{ for 80 kt initial} \end{array}$$

The value of K depends on initial velocity and peak deceleration desired (Figure 22).

Hoffman, W. C. et al: "Navigation and Guidance Requirements for Commercial VTOL Operations". NASA CR 132423, January 1974. (Reference 51)

Study examining civil instrument operations for VTOL, but oriented toward helicopters and compounds. Proposes weather minima approximately one-half of CTOL. Claims helo visual approaches essentially parabolic. Relies on claim that crosswind approaches not a problem (no substantiating data) for CTOL/VTOL mixing. Proposes guidance accuracies of 2 knots horizontal velocity, 0.2 ft/sec vertical velocity in terminal area. Some flight examination using NYA S-61 against MLS -- lateral deviations sensitive, claimed to be function of colocation.

Bathurst, D. B.: "Maritime V/STOL -- The Development of Small Ship Helicopter Operations in the Royal Navy". Society of Automotive Engineers Paper 740820, October 1974. (Reference 52)

Summary of some operational aspects of British Navy helicopter fleet. Current restrictions are 200 feet ceiling, 1/2 mile visibility; ship motion limits are ± 5 deg roll and ± 2 1/2 deg pitch for day, ± 3 deg roll and ± 1 1/2 deg pitch for night. Author claims that pilots must not follow the deck but do "averaging" in head. Night operations require (from ship) glideslope lights, azimuth lights, and horizon bar lights. Helo is radar vectored to get to 400 AGL, 2 nm range at 30° relative bearing, from which he descends at 300 fpm to pick up glideslope lights. In hover beside ship, pilot uses floodlit deck, azimuth, horizon references plus internal cockpit scan, particularly of radar altitude. Helos have downward pointing lights on wheels to assist LSO. New helo (Lynx) uses Harpoon securing device.

Hoffman, W. C. et al: "Display/Control Requirements for VTOL Aircraft". ADI-TR-75-26 (NASA CR 145026), August 1975. (Reference 57)

Analytic study using optimal pilot model to design and propose control/display configurations for NASA CH-47 helicopter. Quadratic synthesis used to design seven control systems for CH-47:

A: no feedbacks
B: p, q, r feedback
C: θ, ϕ, r feedback
D: θ, V_Z, ϕ, r feedback
E: θ, V_Z, ϕ, ψ feedback
F: θ, Z, ϕ, ψ feedback
G: V_X, Z, V_y, ψ feedback
H: X, Z, Y, ψ feedback

Quadratic synthesis using assumed form of director equations used to design longitudinal stick and collective directors for each control system for CH-47. Basic information assumed available to pilot was (X, V_x, Z, V_z, θ, q), with V_x and q being "derived" from display motion.

Concept of using optimal control pilot model was "calibrated" using CH-46 VALT control systems and flight director gains; model predicted inadequate performance without control directors as had been found in flight (although predicted performance with control directors wasn't that much better). Procedure was then applied to CH-47 longitudinal problem with four possible displays:

1. No flight directors
2. Z flight director only
3. X flight director only
4. Both flight directors

The resulting performance and attention workload measures were then normalized into three groups: excellent, acceptable, unacceptable. For hover, the predicted "excellent" combinations were H1, H2, H3, H4, G2, G3, G4 (i.e. translational rate or position control systems), while "acceptable" were G1, F1, F2, F3, F4, C3, C4. Systems D and E were apparently identical, but did not show as acceptable: authors hypothesize a numerical difficulty. Interesting result was more importance of X director than Z for hover.

Stengel, R. F. et al: "The Design of Digital-Adaptive Controllers for VTOL Aircraft". NASA CR 144912, March 1976. (Reference 58)

Study to define digital control laws for CH-47 helicopter. Two types of systems designed:

- Velocity control - all three components
- Attitude command pitch and roll, turn following, vertical velocity command

Control design criteria:

- V_z (both systems): 90% within 2 seconds
  Overshoot $< 5\%$ 0 $\rightarrow$ 10 knots
  $< .5V_x\%$ 10 $\rightarrow$ 40 knots
  $< 20\%$, > 40 knots
- V_x, V_y (velocity command): 80% within 5 seconds
- θ, ϕ, ψ (attitude command): 90% with 1.5 seconds

Designs used proportional -- integral structure and criteria were met over range hover to 160 knots.

Baitis, A. E.: "The Influence of Ship Motions on Operations of SH-2F Helicopters from DE-1052 Class Ships: Sea Trial with USS Bowen". SPO-556-01, July 1975. (Reference 60)

Motion and wind data from sea trials of helicopter-destroyer combination. Found that landings generally occurred at higher ship motions than takeoff. Difficulties in landing occurred for double amplitude ship pitch of 2.2 to 4.0 deg, roll of 4.4 to 11.0 deg. Found that pilots tended to miss lulls in pitch, recommend landing aid to assist. Also show operators in general less successful in determining lulls during more severe motion. Air turbulence caused more difficulty than ship motion. Pilots not too successful in making instant of touchdown coincide with level deck.

Anon: "V/STOL Displays for Approach and Landing". AGARD Report No. 594, July 1972. (Reference 61)

The "Classic" report on helicopter and V/STOL information requirements. Addresses control-display tradeoff concept. Assumes a minimum control system requirement of attitude command in pitch, enhanced weathercock (sideslip) stability, roll attitude command for small inputs and rate command for large inputs, and increased vertical damping; the latter two concepts were, however, considered controversial and requiring more work. It is hypothesized that "Cartesian" coordinates (e.g. decoupled translational rate command) might be good; states strongly that pilot should be relieved of sideslip suppression requirement by SCAS. The following information was listed as essential: airspeed, groundspeed and direction, height (suggested digital plus analog for final 500 feet), vertical speed plus maximum allowable plus desired (e.g. command) value, pitch and roll angle as a compelling display, angle of attack and limits, sideslip or lateral acceleration and limits, range, time (clock), available thrust, thrust inclination (for V/STOL), vertical flight path error, lateral position.

Notes that runway overlay should not be prime landing data source, claim that symbology just as effective. Points out that the number of digital readouts should be kept small. Indicates that height information appears to be the most difficult to present in integrated electronic formats.

Roscoe, S. N. et al: "Advanced Integrated Aircraft Displays and Augmented Flight Control, Volume I". ONR-75-2, June 1975. (Reference 62)

Study to provide background for display and control requirements. Develops "task hierarchy" of pilot which is paraphrase of typical man-in-loop servo structure. Claim is that transformation requirements should be eased for pilot through control-display system. For fixed-wing aircraft, recommends bank-attitude command system, direct vertical velocity control, and automatic turn following to eliminate some inner-loop compensation; simulator showed improvement, but flight did not (primarily because of constant force requirements, as should have been anticipated). Display classification bases:

- "Point of View" (reference coordinates)
- Information coding (TV picture to alphanumeric symbology)
- Manner of display (HUD, HDD: format)

"Literal" display (e.g. periscope, TV) not adequate for landing without additional information. Contact analog (computer generated) recommended as preferable. Claim is that preserving items such as perspective is necessary, however.

Roscoe, S. N.: "Advanced Integrated Aircraft Displays and Augmented Flight Control: Scientific Final Report". ARL-76-17/ONR-76-4, November 1976. (Reference 63)

Summary of studies to "define" control and display augmentation concepts for CTOL. Major emphasis considered to be removing axis transformations required by the pilot. Author advocates perspective skeletal contact analog (meaning orientation and position status data) with predictors and guidance added. Claim is made that steering commands should be pursuit rather than compensatory, although experimental evidence not referenced; "outside-in" problems with pursuit display can be remedied through frequency-separating guidance and status data. Displays use projected flight path and guidance command: put final projection on guidance circle. Author recommends rate-field movement (e.g. "barber poles", typical heading tape) on periphery of displays for airspeed, pitch and roll angles, angle of attack, glide-path angle; this type of display acts as a compensatory command to some extent. Author recommends experimental work to validate theories.

Steinmetz, G. G. et al: "A Piloted-Simulation Evaluation of Two Electronic Display Formats for Approach and Landing". NASA TN-D-8183, April 1976.

Fixed-base ground simulation of TCV Boeing 737 instrument approaches with two EADI formats:

I - ADI and raw localizer, glideslope error.
II - I plus perspective runway, flight path angle.

Addition of runway situation information found to improve both lateral and vertical tracking, "reduce" mental workload.

Dwyer, J. H. III, and E. A. Palmer III: "Three Methods of Presenting Flight Vector Information in a Head-Up Display During Simulated STOL Approaches". NASA TM X-3273, July 1975.

Fixed-base ground simulation of visual STOL approaches with 3 HUD formats differing as follows:

I -- no flight vector information
II -- air-referenced flight vector information
III -- ground-referenced flight vector information

Height tracking performance measures showed some improvement with III, no difference between I and II.

Howard, J. C.: "Measure of Pilot Performance During VTOL Aircraft Landing on Ships at Sea". NASA TM X-73,212, February 1977.

Derivation of relative attitudes and motions between moving ship and aircraft. No data.

Egen, R. A. et al: "Ship-Helicopter System Analysis". AD 774764, December 1973.

"System Analysis" of ships/helos for Coast Guard. Present limits to capability include: limited helo navigational capability, right-lighting problems, lack of adequate night horizon reference.

Bray, G. E.: "Analysis and Design of an Electro-Mechanical Optical Landing Systems for Helicopters at Night in Varying Sea States". NAEC-ENG 7856, May 1976.

Description of visual aid for ships: three-color glideslope indicator (GSI). Green above, amber (1°) at correct glideslope, red below. Light source corrected for ship pitch, roll, heave. Details of mechanical design given. Claim is that lighting system is help at night, but no examples of operational experience given.

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16. Abstract

A survey of research and operational results concerning control-display requirements for helicopters conducting decelerating approaches in the terminal area under instrument meteorological conditions was conducted. In this report, the reviewed programs are organized primarily on the basis of the control augmentation concepts that were considered, and the salient results are summarized and compared. On this basis, nine control-display combinations are hypothesized as possible candidates for future ground and in-flight investigation. Specific guidelines for the guidance relationships, control characteristics, and display presentation concepts, as suggested from the review, are given.

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